TABLE OF CONTENTS

Page

0. **General Introductory Information about the EMTP** iv

- 0.1 **Availability of program to others** iv
- 0.2 Program maintenance and development . . . . iv-a
- 0.3 Program capability (summary) v
- 0.4 Supporting reference material vi
- 0.5 EMTP availability on different computer systems viii
- 0.6 Variable dimensioning of EMTP xiii
- 0.7 FORTRAN data format specifications xviii

1. **Structure of EMTP input data** 1

- 1.0 Cards to begin a new data case (including misc. data cards) . . . 4
- 1.1 Specially-requested extensions to misc. data cards 5
- 1.2 Branch Cards for Linear Branches
  - 1.21 Branch card for lumped series R, L, C 6
  - 1.22 **Branch input using "CASCADED PI" feature** 7
  - 1.23 Branch cards for Pi-Equivalents 8
  - 1.24 Branch cards for mutually-coupled R-L elements 12
  - 1.25 Saturable transformer components 12d
  - 1.26 Branch cards for Distributed-Parameter Transmission Lines 13
  - 1.26a Special double-circuit distributed line 15b
  - 1.26b Frequency dependence for distributed-parameter line (using "WEIGHTING") 16a
  - 1.27 Recursive convolution modeling of frequency-dependent untransposed transmission circuits 16c-1

1.28 Branch cards for pseudo-nonlinear resistance (type-99 branch) 16d

1.29 Branch card for pseudo-nonlinear reactor (type-98 branch) 16g

1.30 Branch card for staircase R(t) (type-97 branch) 16j

1.31 Branch cards for pseudo-nonlinear hysteretic reactor (type-96 branch) 16l

1.32 Branch cards for multi-phase ZnO surge arresters . . 17

1.3 Comments about branch cards for nonlinear and time-varying branches 18

1.35 Branch card for time-varying resistance 19

1.36 Branch card for nonlinear resistance and for lightning arrester 21

1.37 Branch card for nonlinear inductance 24

1.38 Type-94 modern style SiC surge arrester with current limiting gap 25a

1.4 Switch Cards (switches in general) 26

1.40 Ordinary switches 26a

1.41 Switched inductance element (type-93) 29

1.42 Switched resistance element (type-92) 30a

1.43 TACS-controlled switch type-11 for diode and valve application 30c

1.44 TACS-controlled switch type-12 for spark gap and triac application 30f

1.45 TACS-controlled ordinary switch without restrictions on opening current 30h

1.6 Source Cards 31

1.61 Controlled d-c voltage source 34a

1.62 3-phase dynamic synchronous machine source component (Park's equations) 34d

1.63 Universal machine (U.M.) dynamic source component . . . 36f

a year, and finally an Ontario Hydro employee). Vladimir made the switch to regular employment in Toronto during 1978, and has since handled all details related to the conventional S.M. code, whether it be the SCE code, or his own (Type-59) modeling.

2. The Semlyen recursive convolution modeling of Section 1.27a comes from Ontario Hydro (OH) of Toronto, Ontario (Canada). It is named after Professor Adam Semlyen of the University of Toronto, who inspired it (see Refs. 10, 21). Alex Dabuleanu (now deceased; formerly an OH employee) did much of the original work, as a student of Prof. Semlyen. Through the end of 1979, Russell Brierley of OH continued to be the premier expert in use of the feature, and researcher who paved the way for generalization to complex exponentials (theory as per Ref. 21 by Prof. Semlyen). Bob Eifrig of Oregon State University (and a temporary BPA employee for several summers) restructured the original Semlyen code during the summer of 1976 (variable dimensioning, etc.). Then during the summer of 1978, Bob completely recoded the solution code, to allow for an arbitrary number of complex exponentials, following the Ontario Hydro recommendation. Bob did work on the associated new "SEMLYEN SETUP" (prototype which came from Russ Brierley and Vladimir), though a workable production tool never resulted. See Point 9 below.

3. The dynamic surge arrester for SiC devices with active current limiting gaps as described in Section 1.34 was developed and contributed by Chuck Wolf and Dr. Arun Phadke of the American Electric Power (AEP) Service Corporation of New York City.

4. The original mathematical formulation and crude outlines of TACS (see Section 8.), which is used for control system modeling, was developed by Laurent Dube, studying under the supervision of Prof. Hermann W. Dommel at the University of British Columbia in Vancouver. See Ref. 12. Implementation and enhancement in the EMTP were made by Laurent working under contract with BPA. This included the valve and diode modeling of Section 1.43 . Laurent's first BPA contract ended in the summer of 1976, and a second began in the spring of 1979, as a second generation of TACS is being developed. How much of the new goodies make the general distribution during the summer of 1980 is not now (March, 1980) clear.

5. Professor Akihiro ("Aki") Ametani of Doshisha University in Kyoto (Japan) developed the "CABLE CONSTANTS" code of Section 7.7 ; and he also inspired the "Ametani linear convolution" modeling of Section 1.27b (see Ref. 11), the implementation of which was designed and performed by Bob Eifrig.

6. The Type-96 hysteretic inductor modeling of Section 1.31 was developed by Prof. Narendra ("Ned") Mohan and Mr. Jim Frame of the University of Minnesota in Minneapolis. This was during 1978 and 1979, under contract with BPA.

7. The universal machine (U.M.) modeling of Section 1.63 was developed by Prof. Hian Lauw of Oregon State University in Corvallis, Oregon. This was during 1979 and 1980, under contract with BPA.

8. The Type-59 dynamic synchronous machine (S.M.) modeling of Section 1.62 was originally researched by Dr. Vladimir Brandwajn while studying for his doctorate in Vancouver (another of Prof. Dommel's graduate students). See Ref. 15. Implementation in the EMTP was under contract with BPA (see Ref. 8, Vol. VII, 23 December 1977, pagination CBVB). In 1978 Vladimir joined Ontario Hydro in Toronto, and has been refining and extending the code ever since.

9. Dr. John Hauer of BPA joined the EMTP development effort during the late fall of 1979, to rescue our suspended "SEMLYEN SETUP" work. See Ref. 8, Vol. IX, 4 October 1979, page EDTO-1 . Rather than correcting past work, he is putting in his own self-contained, sophisticated, frequency-domain fitting program that has evolved over the past decade or two. John says that this is a case of transfer of technology, of applying standard simulation techniques of the control and aerospace industries to power systems. Work is still underway in April of 1980.

Hence there is quite a bit of EMTP competence which is spread around among a number of individuals. The effort was long ago bigger than any one person, group of persons, or even power pool. Industry-wide development on an international scale is now going on, though based only on informal committments among organizations, and short-term contracts with individuals. The coordination has been centered largely in Portland (BPA), if only by default. The possibility of better coordinated and better funded development is now being pursued; any progress shall be reported in the EMTP Newsletter. To get an idea of what is being proposed, see Ref. 8, Vol. IX, 6 August 1979, pagination FYTM.

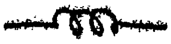
A new EMTP user is encouraged to seek assistance within his own company when using the program for the first time, or when using it in a new mode. If there are questions as to program and/or problem restrictions, an inquiry to experienced personnel is almost always advisable. The EMTP and associated problem modeling are inimitably tricky and sophisticated, with experience invaluable in order to avoid experimentation of a trial and error (garbage in, garbage out) nature. For those able to spend corporate funds, and able to travel to Madison, Wisconsin, I strongly recommend the EMTP short course (see beginning of section).

Finally, Program Maintenance at BPA would like to be informed of program bugs (errors), of course. If after having very, very carefully double-checked his input data and physical modeling assumptions, the user is willing to carefully and clearly document his difficulty, then Program Maintenance at BPA would indeed appreciate hearing from him. This goes for users outside BPA as well as internal users, provided they are using the latest available production version (or translation) of the program. In general, it is only program bugs which show up in the latest production version of the EMTP which can be the concern of Program Maintenance. Outside (non-BPA) users are completely on their own, then, unless they remain current by periodically procuring a new version of the EMTP when major production updates are performed.

0.3 Program Capability (Summary)

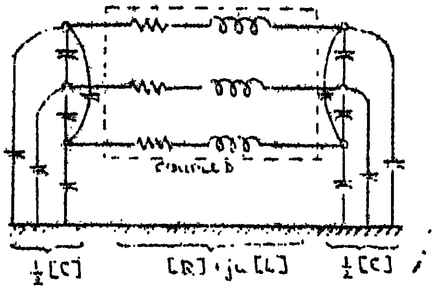
The Transients Program is used to solve the ordinary differential and/or algebraic equations associated with an "arbitrary" interconnection of the following elements:

1. Lumped resistance: $v = R i$

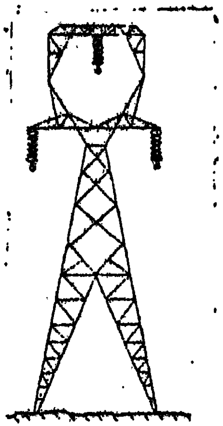
2. Lumped inductance:  $v = L\, di/dt$

3. Lumped capacitance: $i = C\, dv/dt$

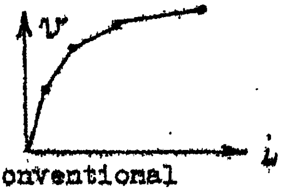
4. Multiphase Pi-equivalents, where the preceding scalar R, L, C become symmetric square matrices [R], [L], [C].



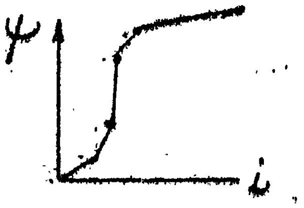
5. Multiphase distributed-parameter transmission lines, wherein propagation time of the line is represented. Distortionless and externally-lumped-resistance approximations are available, as well as "exact" frequency-dependent representations.



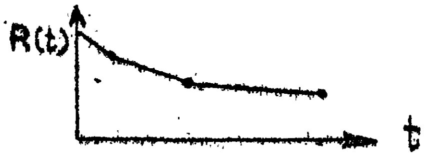
6. Nonlinear resistors, where the curve must be single-valued.



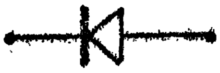
7. Nonlinear inductors, either with the conventional single-valued characteristic (see sketch at right), or including hysteresis.



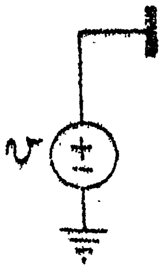
8. Time-varying resistance.

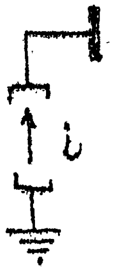


9. Switches, used to simulate circuit breakers, lightning-arrestor flashover, or any other network connection change. Diodes and dc converter valves are included

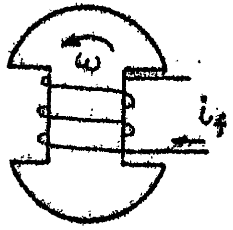


10. Voltage or current sources. In addition to standard mathematical functions (sinusoids, surge functions, steps, and ramps), the user may specify sources point by point as functions of time, or in FORTRAN, or as defined by TACS (see Point 12 below).

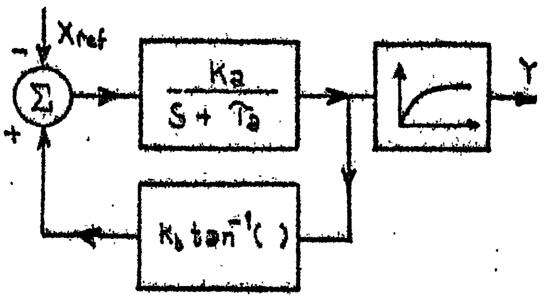




11. Dynamic synchronous machines (3-phase balanced design only). The electrical side is represented by Park's (Blondel's) equations, while the mechanical side is modeled as an interconnection of masses, springs, and damping. Arbitrary exciter and governor dynamics can be represented, by connection to TACS (see Point 12).



12. Control system dynamics, as are normally represented on differential analyzers (analog computers). This modeling capability goes by the name of TACS (an acronym for Transient Analysis of Control Systems). Nonlinear and logical operations may be represented. Input and output may be interfaced with the electric network of the EMTP, providing a hybrid representation. All TACS representation is user-patchable, and hence configuration free. See Sect. 8.



13. Unconventional rotating electromechanical energy converters of various sorts, including induction machines and dc machines. An arbitrary number of windings on each rotor axis is allowed, there is no restriction to 3-phase usage, etc. Compensation is used, and any mass-spring dynamics of the shaft are represented by an electrical analog. Various control system connections are possible, via TACS. Refer to Section 1.63 (the universal machine model).

Trapezoidal-rule (second order) implicit integration is used on the describing equations of the component elements so as to form an associated set of real, simultaneous, algebraic equations which must be solved at each time step.[1] These are placed in nodal-admittance form (with new unknown voltages as variables), and are solved by ordered triangular factorization.[4] The user is referred to references 1, 2, and 3 below for the mathematical details.

Program output consists of voltages and currents as functions of time, for those variables requested by the user. Both printed and plotted output are available. Interactive CRT plotting of results is also available on some systems, and is clearly the superior mode of output when properly set up and supported. Details of a CDC-Tektronix system are covered in a January 25, 1975 EMTP memoranda of Reference 8. See Section 5.0 for a general summary.

Initial conditions for the differential equations can be determined automatically, provided that all sources are sinusoidal, and of the same frequency. Such phasor solutions can also be printed out, as per Section 1.0h. As a case can be terminated after such a solution, the Transients Program thus serves as a (linear) ac sinusoidal steady-state program also.

0.4 Supporting Reference Material

Theory behind the EMTP is scattered through various technical papers and a few books. The following may be found useful for reference purposes:

1. H. W. Dommel, "Digital computer solution of electromagnetic transients in single and multiphase networks," IEEE Trans., vol. PAS-88, pp. 388-399, April 1969.

2. H. W. Dommel, "Nonlinear and time-varying elements in digital simulation of electromagnetic transients," IEEE Trans., vol. PAS-90, pp. 2561-2567, Nov/Dec 1971.

3. W. S. Meyer, H. W. Dommel, "Numerical modelling of frequency-dependent transmission line parameters in an electromagnetic transients program," IEEE Trans., vol. PAS-93, pp. 1401-1409, Sep/Oct 1974.

4. W. F. Tinney, J. W. Walker, "Direct solutions of sparse network equations by optimally ordered triangular factorization," Proc. IEEE, vol. 55, pp. 1801-1809, November 1967. Also available in 1967 IEEE PES PICA Conference Record.

5. User's Manual for BPA Line Constants Program. No longer available separately, this is now part of the EMTP (see Section 7.4).

6. M. Javid, E. Brenner, "Analysis, Transmission, and Filtering of Signals." New York: McGraw-Hill, Chapter 11, 1963.

7. H. W. Dommel, W. S. Meyer, "Computation of electromagnetic transients," Proc. IEEE, vol. 62, pp. 983-993, July 1974.

8. W. S. Meyer, "Transients Program Memoranda." Approximately 150 pages per volume, this concerns the EMTP development memoranda which are regular issued as progress is made. Individual memos are bound when there has been sufficient accumulation to form a volume. As of March of 1980, there were nine volumes. Only the most recent volume is generally available, however, so do not write requesting a complete set. Older volumes are out of print. When a new volume is released, a fixed number of copies are printed; and when these are exhausted, the volume becomes unavailable through regular channels (a Freedom of Information request would always be honored, of course, but a copying fee would be charged).

9. D. R. Carroll, W. S. Meyer, "Digital and hybrid computation of electromagnetic transients in power networks," Sixth Annual Pittsburg Conference on Modeling and Simulation, Pittsburg, Pennsylvania, April 1975.

10. A. Semlyen, A. Dabuleanu, "Fast and accurate switching transient calculations on transmission lines with ground return using recursive convolutions," IEEE Trans., vol. PAS-94, pp. 561-571, 1975.

11. A. Ametani, "A highly efficient method for calculating transmission line transients," IEEE Trans., vol. PAS-95, pp. 1545-1551, Sept/Oct 1976.

12. L. Dube, H. W. Dommel, "Simulation of control systems in an electromagnetic transients program with TACS," IEEE PES PICA Conference Record, vol. 10, pp. 266-271, 1977.

13. W. S. Meyer, "Machine translation of an electromagnetic transients program (EMTP) among different digital computer systems," IEEE PES PICA Conference Record, vol. 10, pp. 272-277, 1977. See also Ref. 8, Vol. VI, 5 January 1977, pagination PICA.

14. V. Brandwajn, H. W. Dommel, "Synchronous machine parameters in analysis of electromagnetic transients," Canadian Communications and Power Conference, Montreal (P.Q., Canada), October 20-22, 1976.

15. V. Brandwajn, "Synchronous Generator Models for the Simulation of Electromagnetic Transients." Ph.D. thesis written at the University of British Columbia (Vancouver, B.C., Canada), April 1977, 117 pages plus preface.

16. G. Gross and M. C. Hall, "Synchronous machine and torsional dynamics simulation in the computation of electromagnetic transients," IEEE Trans., vol. PAS-97, pp. 1074-1086, July/Aug 1978.

17. D. P. Carroll, R. W. Flugum, J. W. Kalb, and H. A. Peterson, "A dynamic surge arrester model for use in power system transient studies," IEEE Trans., vol. PAS-91, pp. 1057-1067, May/June 1972.

18. IEEE SSR Task Force, "First benchmark model for computer simulation of subsynchronous resonance," IEEE Trans., vol. PAS-96, pp. 1565-1572, Sept/Oct 1977.

19. P. M. Anderson, A. A. Fouad, "Power System Control and Stability." Ames, Iowa (USA): The Iowa State University Press, 1977.

20. V. Brandwajn, H. W. Dommel, "A new method for interfacing generator models with an electromagnetic transients program," IEEE PES PICA Conference Record, Vol. 10, pp. 260-265, 1977.

21. A. Semlyen, "Contributions to the theory of calculation of electromagnetic transients on transmission lines with frequency dependent parameters," paper submitted to IEEE for presentation at the 1979 PES Summer Meeting.

22. H. W. Dommel, Editor, "EMTP Newsletter." Published approximately quarterly in Vancouver, issue number one appeared during July of 1979. For information about subscription, write to: Dr. Hermann W. Dommel, Professor; Electrical Engineering Dept.; University of British Columbia; Vancouver, B.C. V6T 1W5; CANADA.

23. V. Brandwajn, W. S. Meyer, H. W. Dommel, "Synchronous machine initialization for unbalanced network conditions within an electromagnetic transients program," IEEE PES PICA Conference Record, vol. 11, pp. ???-???, 1979. Also available in Ref. 8, Vol. VII, 28 January 1978, pages TDCE-13 through 16.

24. H. W. Dommel, B.C. Chiu, W. S. Meyer, "Analyzing transients in ac/dc systems with the BPA Electromagnetic Transients Program," Proc. IEEE International Conference on Overvoltages and Compensation on Integrated ac-dc Systems, Winnipeg, Canada, July 8-12, 1980.

25. A. Ametani, "A general formulation of impedance and admittance of cables," IEEE Trans., vol. PAS-99(3), pp. 902-910, 1980.

26. A. Ametani, "Wave propagation characteristics of cables," IEEE Trans., vol. PAS-99, No. 2, pp. 499-505, March/Spril 1980.

27. R. H. Lasseter, D. M. Demarest, F. J. Ellert, "Transient Overvoltages on the neutral bus of HVDC transmission systems," IEEE PAS paper No. A78 707-4, presented at the 1978 Summer Meeting.

28. R. H. Lasseter, "Electrical characteristics of long overhead HVDC transmission lines," IEEE PAS paper No. A79 535-6, presented at the 1979 Summer Meeting.

29. IEEE Tutorial on the digital computer solution of electromagnetic transients. Just now (September, 1980) being prepared, this is tentatively scheduled for the Winter (Atlanta) and Summer (Portland) Meetings of the Power Engineering Society. The session is to last one full day, and there is to be a printed booklet consisting of six IEEE-type papers on different aspects of the subject. With something like 150 references of its own, and ample historical perspective in several papers, the printed transcript is recommended for beginners and management (who may want a carefully-prepared overview of the subject).

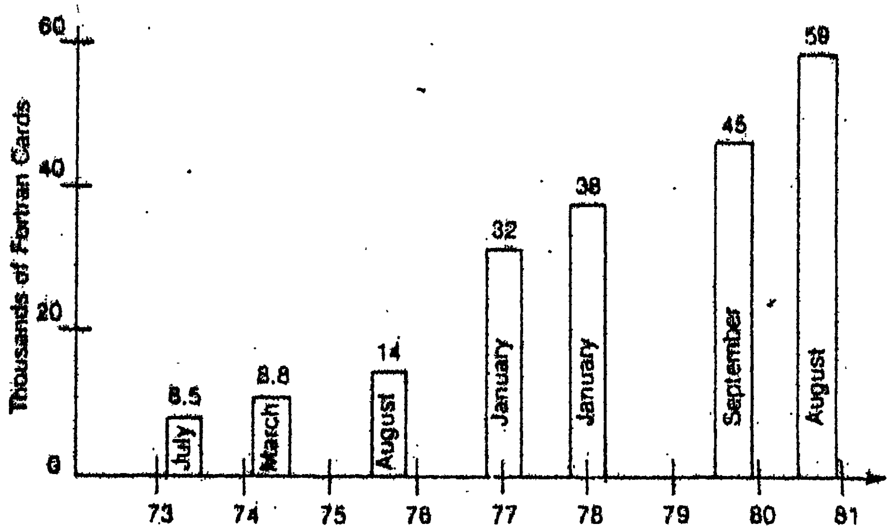


Fig. 29. Growth of EMTP (actually, UTPF) code vs. time.

0.5 Program Availability on Different Computer Systems and Installations

The EMTP is being made available for execution on the different major American computer systems by means of machine translation of an installation-independent master file known as the Universal Transients Program File (abbreviated UTPF). Conceived of in November of 1974 (see Ref. 13), this scheme utilizes a different Editor/Translator (E/T) program for each different computer system, so as to machine-process the UTPF, to convert it into legal EMTP FORTRAN for the particular installation of interest. Thus all EMTP code actually begins with the same master file (the UTPF), but differs according to the built-in or specially-requested properties of the translation. Within this framework, the writing of a common EMTP User's Manual for all is thus a little bit tricky.

Some differences of the EMTP code for different computer systems are completely hidden, out of sight of the program user, and are of no concern to him. For example, alphanumeric storage (e.g., the 6-character names for network busses) on Univac is handled in FORTRAN INTEGER variables, while on IBM the mode is REAL*8 . This is a concern of the program developers only, not of any normal interest to the user. Reference 13 summarizes the entire process.

Other machine differences affect the user in only a minor way, and he may not even initially be aware of them. For example, computer word length dictates certain precision or other numerical requirements on the input data. Control Data with its big 60-bit word is more tolerant of a wide disparity of input data than is Univac with its 36-bit word, for example. Here we are talking about limits which exist for all EMTP users, but which vary in severity or value according to the computer installation being considered. Relevant comments about such considerations will be found in the user instructions, where appropriate. The user should always be aware of the computer word length used in his EMTP translation, needless to say.

Finally, certain EMTP operations are totally different for different installations, at least in outward appearance, as far as the user is concerned. For example, computers of different manufacture (IBM, CDC, Univac, SEL, etc.) will require completely different job control cards, in general. These are the instructions by means of which one pleads with the installations operating system, asking for the EMTP, manipulating his data input files and the program output. Such job control language (JCL) may even vary among different installations of the same manufacturer, due to local preferences or constraints which are placed on the mode of operation. If in doubt as to what to employ, the user should always contact his resident EMTP expert for the last word. Yet as a general guide, the following "system" instructions as to EMTP setup are typical, for the different computer systems indicated: Refer to Section 0.5a onward --- that section applicable to the computer system of interest.

As summarized in Reference 13, FORTRAN statements which are highly dependent on computer manufacturer and/or installation usage have been isolated in installation-dependent EMTP modules. If a given organization performs its own translation, such modules will be set up to satisfy its own peculiar needs, and Program Maintenance of that organization should thoroughly understand the decisions which have been made; in this case, there should be no complication at all. But, if a given organization receives a FORTRAN copy of the EMTP from some other group which uses a computer of the same manufacture, then perhaps nothing will be known about installation-dependent modules and the installation-dependent choices which may have been made therein. In order to be able to change some of these decisions if need be, the user must know how to locate such modules. The following is a list as of April, 1980 ("M27." idents):

Module name	UTPF overlay name and #	Purpose of module
EREXIT	MAIN00; -1	For those systems which can recover from fatal system errors, set up the linkage in this module.
RUNTYM		Find the current central processor and input/output job times.
TIME44		Find the current wall-clock time, in format "HH.MM.SS".
CIMAGE		Read the next data card from unit LUNIT5. DECODE it as 80A1 if free-format. Check for $-cards. Skip over comment cards, etc.
LOCF		Find the address in memory of the argument, as a number of REAL words.
LOCINT		Find the address in memory of the argument, as a number of INTEGER words.
RFUNL1 RFUNL2 RFUNL3 CFUNL1 CFUNL2 CMPLXZ IFUNL2 IABSZ		All library functions are defined using ENTRY points in these modules, for those systems allowing ENTRY usage. Neutral names are used (e.g., "SINZ" is used for the usual "SIN" or "DSIN"). Special limit checking can also be placed in these modules.
PACKA1		Packs one character (A1 information) of one word into any character position of another word.
PACKCH		Packs A4 or A6 word strings into ALPHANUMERIC vector storage so that there are no imbedded blanks. This was originally designed for CalComp plotting, to remove excess blanks.
SEEDY		Find the number of seconds since midnight, based on alphanumeric input of the time ("HH.MM.SS").
RANDNM		Compute a random number (roll the dice), uniformly distributed over the unit interval (0, 1).

SYSDEP	OVER1 ; 1	Performs various system-dependent initializations at the start of execution of a new EMTP data case.
MIDOV1		Performs miscellaneous system-dependent initializations when EMTP control is ready to exit OVER1 . The call to SYSDEP is too early to perform all system-dependent initializations, it turns out.
DATE44		Find the calendar date ("MM/DD/YY").
PFATCH		Attach (connect) a disk file of plot points to I/O unit LUNIT4 , in conjunction with "REPLOT" usage of Section 1.0d .
DLIBRF	OVER13 ; 13	Used to provide double-precision library functions just within overlay 13, for use with the Semlyen recursive convolution code only.
KATALG	OVER20 ; 20	Save the contents of unit number LUNIT4 as a permanent file on disk. File is later used with for "REPLOT" (Section 1.0d) or interactive plotting (Section 5). But such usage is only for those systems (e.g., BPA-modified CDC) where it is possible to catalog after the file has been written. For those systems requiring the cataloging before anything is written in the file (e.g., Honeywell, VAX), use SYSDEP instead.
STATRS	OVER29 ; 29	This module serves to connect to units LUNIT3 and LUNIT9 the "STATISTICS" results which were previously saved on disk by STATSV . This is in response to "TABULATE ENERGIZATION RESULTS" request of Section 1.07 .
BEGPLT	OVER31 ; 31	Module is called by the main plotting module SUBR31 before any CalComp plotting is done, for each data case. Arbitrary system-dependent initialization is possible.
ENDPLT		Module is called by the main plotting module SUBR31 after all plotting of a given data case is completed. Arbitrary system-dependent termination (e.g., buffer flushing) is possible.

FINTP		Module is called immediately before the one and only (almost) STOP statement of the EMTP. Arbitrary termination operations (e.g., file closing, spooling, etc.) can be performed.
ROUND	OVER41 ; 41	Possibly installation-dependent. This module rounds a floating-point number to five significant digits. The universal module uses logarithms as a scientific approximation. For those having DECODE, and a penchant for purity (we at BPA do not), replacement could be made.
MIDO48	OVER48 ; 48	The "HAUER SETUP" feature (see Sections 7.8 and 7.9) uses various I/O channels in different modes (FORMATTED vs. UNFORMATTED reads and writes) than for all other EMTP features. For systems like VAX which require that the mode be declared when the file is opened, this module closes the SYSDEP openings, and reopens as needed.
STATSV	OVER55 ; 55	Save the contents of units LUNIT3 and LUNIT9 at the end of a "STATISTICS" data case, to allow for later tabulation (usually with the addition of other partial results). See the "STATISTICS OUTPUT SALVAGE" feature of Section 1.0? . As with KATALG , this is for systems (e.g., BPA CDC) which permit cataloging after the fact. For those systems (e.g., Honeywell and VAX) which require cataloging before, use MIDOV1 instead.

APPENDIX : There may, or may not, be a module "FRENUM" in overlay -1. If it appears, it is installation-dependent, and is called by "FREFLD" to actually extract a free-format numerical number. See Ref. 8, Vol. X, 3 July 1980, page MSDO-11. If not used, the universal "FREFLD" of "M27," and earlier versions is being relied on, and precision might be questionable. Read the EMTP memo for details.

Several specific modifications will be of concern to many installations, particularly those which are not in the U.S.A. (where conventions are different). Included are the following:

1. Power system (synchronous; steady-state) frequency

The steady-state frequency of power system operation is defined within module "SYSDEP" of overlay number 1. Variable "STATFR" should be assigned this frequency in Hertz (equal to 60.0 for usual usage within the United States).

2. Calendar date format

As set up for usage in the States, "MM/DD/YY" is printed, where:

"MM" ---- two decimal digits for the month (e.g., "03" for March);
"DD" ---- two decimal digits for the day within the month;
"YY" ---- two decimal digits for the year (e.g., "77" for 1977).

In most other parts of the world (including Canada, as I recall), and even in the U.S. Army, I believe that it is common usage for the day "DD" to precede the month "MM". If module "DATE44" (see above chart) is altered so as to produce "DD/MM/YY", then the associated format within subroutine "SYSDEP" (which is used for one or two lines of EMTP heading) should be changed accordingly.

3. Free-field data format characters

As explained in Section 1.0g6, two special characters are used in conjunction with EMTP free-field data input. As of April 1980 ("M27." UTPF idents), a comma is the default separator character "CSEPAR" and a dollar sign is the default continuation character "CHCONT". If local Program Maintenance wants to alter these, it is a trivial matter to change these variable definitions within module "SYSDEP" (see above chart). The only restriction should be obvious: both characters must be unique and distinct from all EMTP data characters. For example, a slash ("/") could not be used along with a data case which involved TACS supplemental variables, since "/" is used to indicate division in Section 8.5.5 data.

4. Batch-mode plotting parameters

Several parameters which are related to batch-mode EMTP plotting (Section 1.10) are defined in module "SYSDEP" (see above chart). The following might be varied, from one installation to another:

SZPLT ----- Height of CalComp plotting paper which is being used, in inches. Or more precisely, this is the maximum vertical excursion of the pen (any margin and sprocket holes thus are not to be counted). Recall that the user is able to over-ride this default value at execution time, using a "PLOTTER PAPER HEIGHT" card of Section 1.0e, SZBED —— Maximum length of the plot, in inches. For BPA CDC usage, this is set equal to 72.0 (about the size of our EAI flatbed surface). This parameter is used as an argument of the overlay #31 call to subroutine "PAPRSZ" (whose job it is to protect against illegal excursions of the pen).

LNPIN —— The number of lines per inch of the line printer. Recall that the scaling of a line printer plot will depend on this figure. The user is able to over-ride the default value at execution time, using a "PRINTER LINES PER INCH" card of Section 1.0c .

NSMTH —— The number of successive ups and downs before averaging of successive points is resorted to, for plot purposes. Recall that the user is able to over-ride this default value at execution time, using a "LIMIT ON PLOT OS" card of Section 1.0c .

LLBUFF —— Variable which is used as the second argument of the call to CalComp subroutine "PLOTS" —— to be found within module "BEGPLT" (see above chart) of overlay #31. As originally used by CalComp a decade or so ago, this was the buffer length of the "LUNIT8" output chanel on which plotter instructions will be written. But many installations no longer use such a specification (e.g., the buffer may be automatically set by the system, or it may be defined by the job control language (JCL) cards).

The first executable statement of the program, located in "MAINOO" (overlay number -1) and never executed again, is the assignment of value -3333 to "LLBUFF" . The first time through "SYSDEP" , this is converted to a positive value. Module "BEGPLT" of overlay #31 then could append a minus sign, as a flag that "PLOTS" has been called once, and is not to be called again —— if this is the desired usage. Remember, batch-mode plotting is done by a primary-level overlay, if the program is overlaid. For BPA CDC, this requires that "PLOTS" be called each time the overlay is used (for each data case which uses CalComp plotting). This seems to be quite installation dependent.

5. Input/output unit numbers

Unless explicitely altered to the contrary by Program Maintenance which sets up the translation, the following input/output (I/O) unit assignments will be assumed:

LUNIT5 = 5 ----- card reader (EMTP input data cards)

LUNIT6 = 6 ----- line printer (EMTP printed output)

LUNIT7 = 7 ----- card punch (for EMTP punched-card output)

LUNIT8 = 8 ----- machine-language instructions for plotting hardware (as generated by calls to the Calcomp subroutines during the overlay #31 batch-mode plotting)

LUNIT1 = 1 ----- scratch tape; very small buffer will suffice (for BPA CDC, 64 decimal words were used).

LUNIT2 = 2 ----- scratch tape which is used for dumping most of /BLANK/ and /LABEL/ , to be read back into central memory for each new energization of a "STATISTICS" or "SYSTEMATIC" data case. A big buffer is recommended (for BPA CDC, a buffer of 1024 decimal words was used).

LUNIT3 = 3 ----- Like "LUNIT1"

LUNIT4 = 4 ----- scratch tape which is used for storage of the raw data points of the plot file (later to be plotted). A good size buffer is recommended (for BPA CDC, we used 512 decimal words).

LUNIT9 = 9
:
LUNIT15=15 } ----- like "LUNIT1"

If any of these usages are illegal or inconvenient at the installation of interest, alternate assignments should be made within module "SYSDEP" (see above chart). PRIME is one such system, for which some re-assignments had to be made. Actually, as of April, 1980, I do not believe that "LUNIT10" through "LUNIT16" are actually being used for anything other than possibly the "HAUER SETUP" code of overlays 48 and 49.

0.5a Control Data EMTP Setup (as used at University of Minnesota)

Before February of 1979, BPA used Control Data Corporation computer systems for the support of the EMTP, and there were elaborate instructions related to use of the CDC EMTP in this section. But this ended with acquisition of BPA's DEC VAX-11/780 (see later section), and BPA EMTP usage of CDC has ceased. Do not write to BPA for a CDC version of the EMTP, since current CDC EMTP versions no longer even exist in Portland.

The University of Minnesota in Minneapolis seems to be the dominant remaining domestic CDC user which has EMTP interest. An "M27." version was set up there during May and June of 1980, and the CDC Editor/Translator (E/T) program was converted from VAX to CDC (see Ref. 8, Vol. IX, 17 June 1980, page TTMA-11). Everything would seem to be in place, ready for the general EMTP release of the summer or fall of 1980. It is this upcoming version which shall be made available to the general public for a modest charge (something like $300 is now being contemplated, to cover the cost of program setup, testing, a new tape, handling, and postage). The key individual in the plan is a long-time EMTP user, to whom all questions should be directed:

Dr. Narendra ("Ned") Mohan, Professor
Electrical Engineering Department
123 Church Street S.E.
University of Minnesota
Minneapolis, Minnesota 55455
U.S.A. Telephone: (612) 373-5419

Back to technical aspects of the service which Ned has offered to provide. A new reel of magnetic tape (most likely not over 1200 feet at most) shall be used, so do not mail any scratch tapes to him. As for tape format, 9-track, 1600-BPI, labeled, and SI (System Internal) Format are understood to be applicable adjectives. This latter specification implies a binary tape, I guess (created by COPYBF or COPY commands). Tapes shall be mailed by First Class in the USA and Canada, and by Air Mail to all other countries.

CDC CDC CDC CDC CDC CDC CDC CDC CDC CDC CDC CDC CC

Minimum contents of the tape shall be the following files:

1. UPDATE SOURCE file of "VARDIM" FORTRAN. This is the variable-dimensioning program.
2. UPDATE SOURCE file of EMTP proper. This is the CDC EMTP FORTRAN.
3. UPDATE SOURCE file of a number of sample EMTP data cases.
4. OUTPUT (line printer) file of the solution to a number of sample EMTP data cases.

Unlike past CDC EMTP distributions which were made by BPA, this time the user should not have to worry about special installation-dependent modules that are peculiar to the distributor. It seems as though the calendar date and time of day are now available using standard CDC library functions, so no problem here. As for the LUNIT4 plot file, it was decided to have the user handle this himself, externally, as part of his job control cards. That is, there is no internal OPEN or CLOSE operation for this file. As long as the user only solves one data case at a time, and is willing to keep track of plot file names individually, this works. General structure of CDC NOS job control cards for a typical EMTP solution then have the following general form:

```
1. Job card (time and memory limits, etc.)
2. Account card (user authorization)
3. ATTACH(TPOVERL)
4. TPOVERL.
5. REWIND(TAPE4)
6. RETAIN(TAPE4=  file name (7 characters or less)
7. 7-8-9 card (end of file card)
8. BEGIN NEW DATA CASE

        EMTP data case being solved.

9. BEGIN NEW DATA CASE
   BLANK CARD ENDING DATA CASES.
```

For those production-oriented users who would prefer to have the LUNIT4 plot file internally opened, this is possible using FORTRAN V CDC software (it will not work with FORTRAN IV). The required additional code will be found within module "PFATCH" of UTPF overlay number one (CDC UPDATE ident "OVER1"), with "C" added to column 1 to produce comment cards. This is the opening operation. As for closing, this is in "SYSDEP" of the same overlay, also commented out. Execution of this added logic was tested in Minneapolis using a separate driver, so it should work.

As for CalComp EMTP batch-mode plotting, little can be said. If the recipient wants to use this, he must supply his own plotting subroutines (AXIS, SYMBOL, etc.) when he LOADs the EMTP. Such externals can be left unsatisfied, if such plotting is never to be used. If an I/O unit number

CDC CDC CDC CDC CDC CDC CDC CDC CDC CDC CD

is required for the plot file, TAPE7 has been reserved for this purpose. The user of CalComp EMTP plotting is also referred to the section "4. Batch-mode plotting parameters" preceding Section 0.5a .

The status of interactive CRT plotting for CDC is still uncertain. Refer to Section 5. for an explanation of the concept. As of June 1980, no commitment has been made to convert the BPA VAX program to CDC.

The preceding page illustrated sample job control cards for the solution of an EMTP data case, including the saving of LUNIT4 plot data points on disk as a permanent file. If batch-mode EMTP plotting of this file is desired at a later time, then the following job structure is applicable:

1. Job Card
2. Account card.
3. ATTACH(TAPE4= file name)
4. ATTACH(TPOVERL)
5. TPOVERL.
6. 7-8-9 card.
7. BEGIN NEW DATA CASE
   REPLOT

   Batch-mode plot cards of Section 1.10, ended with a blank card.

   BEGIN NEW DATA CASE
   BLANK CARD ENDING DATA CASES.

Some CDC users may have a shortage of user-available Central Memory (we at BPA did), so a few words about memory requirements might be in order. No Extended Core Storage is used at all. As for Central Memory, CM160000 should be adequate to solve most typical production problems that are of interest to a utility, though the variable dimensioning program "VARDIM" may have to be used from time to time in order to trade the space of one table off against another. Based on "M27." experience, about 37K decimal words are required just for the code (37.4K decimal = 111K octal), though this ignores the fixed storage which is required by features which have yet to be variably-dimensioned (S.M. code, and ZnO code). If tables of /LABEL/ were set to zero, CM123360 would be required, so variable dimensioning really begins from this base. "CABLE CONSTANTS" is a special case requiring fixed storage if it is used, something like CM160000 .

CDC CDC CDC CDC CDC CDC CDC CDC CDC CDC CDC

0.5b IBM EMTP Setup (as used at AEP in New York City)

Previous EMTP versions for IBM ("M21." and earlier) were set up, tested, and distributed by General Public Utilities in Reading Pennsylvania. But then in March of 1979 there was the Three Mile Island nuclear accident, and the service had to be dropped as an austerity measure. That was Roger LeVesque and his colleagues.

Well, the American Electric Power (AEP) Service Corporation has come to the rescue. In addition to continuing with the distribution of those "M21." GPU materials, AEP has agreed to handle the setup and distribution of a new IBM EMTP version during the summer of 1980. Yet it is now (March, 1980) too early to provide any details as to format, assumptions, procedures, etc. However, the individual who will be responsible at the working level for these decisions can be indicated:

Mr. Michael Price, Room 1983
Computer Applications Division
American Electric Power Service Corp.
Two Broadway
New York, New York 10004
U.S.A. Telephone: (212) 440-9359

While not in any way to be interpreted as an AEP committment, I might just pass along my own guess as to probably specifications. First, the computer used is an IBM 3033, and tapes will be copied as 9-track, 1600-BPI, EBCDIC. The IBM EMTP will most probably be overlayed (just as the "M21." version of GPU was). As with the GPU "M21." materials now being distributed, there will be no charge for domestically-based parties who send them a tape without any financial or bureaucratic (e.g., Customs) encumberment. As for overseas parties who have no friends in the USA, some sort of arrangement will be made, though this is still being discussed. It makes no economic sense to mail a reel of tape from overseas, so 1200-foot reels will be purchased here, and this cost and that for postage will be charged to the individual wanting the program. But just who might provide this service is not yet known (do not assume that it will be W. Scott Meyer, just because he did it two years ago!).

==

On 7 May 1980, Mike Price telephoned to indicate an important restriction. Due to their remote operation (computers are located in Ohio) and standardized tape-handling procedures, Mike says that AEP must insist on a labeled tape. Any tape mailed to him in conjunction with a request for EMTP materials must be initialized with a standard IBM label, 9-track, 1600-BPI. If they are not so labeled, the standard AEP tape-copy procedure will abort, and the tape will be returned to its owner without any materials having been recorded on it. So, IBM parties, observe this restriction!

AMERICAN ELECTRIC POWER *Service Corporation*
AEP
2 Broadway, New York, N.Y. 10004
(212) 440-9000

X-C

0.5c Univac EMTP Setup (as used at Ontario Hydro in Toronto, Ontario, Canada

A job submitted for batch processing on our Univac 1110 would start with a 'RUN' card which contains job priority, user identification, account identification, project number, max time, max pages. This card is installation dependent, and will not be described in detail here.

The user is reminded, though, that if a plot is attempted, the program will automatically assign a magnetic tape on which to store the plot information. One must not, under this circumstance, be caught using a priority which will not permit tape assignments.

If the user intends to punch cards, remember that the default max card limit is 100. If more cards are expected, then a larger max card limit is supplied as a / addition to the MAX PAGE field.

EMTP execution on Univac within existing fixed program dimensions

If the user's data is expected to fit the normal program size, execution of the program requires only the following control cards:

1. @RUN described above.
2. @ASG,A U-RHB*LIBS. This card assigns a catalogued file containing the program's absolute element.
3. @XQT U-RHB*LIBS.TRANSIENTS This card starts execution of the program, and is followed by the data cards described elsewhere.
4. @FIN This card terminates program execution.

The saving and/or recovery of old plot-data-point files

Our particular machine software permits permanent cataloguing of files. If the ICAT key is set to 1 or 2 (see 1.0h Miscellaneous Data Parameter Cards), the program will automatically catalogue a file using PROJECT-ID information on the Run card as QUALIFIER, with a file NAME consisting of 12 numbers indicating the date and time of the start of the particular study. This date and time appears on the printed output associated with each study.

If a subsequent study is started in the same run, the original file will be freed (detached from the run) to prevent overwriting of the data. A new file will be assigned, temporary

UNIVAC
UNIVAC
UNIVAC
UNIVAC
UNIVAC

or catalogued, dependent on th ICAT key of this study

If a 'REPLOT' is requested (see 1.0d - Calcomp Plotting of Previously-solved Cases), the catalogued file containing the data will be automatically assigned providing the correct file name is supplied on the REPLOT request card. Contrary to the CDC instructions, the file name must be left justified in the field, and will usually be of the form QUALIFIER*MMDDYYHHMMSS. where the QUALIFIER is the account field of the Run Card used to produce the file in the first place. Note that no '/' or '.' is contained in the MMDDYYHHMMSS list since on Univac these symbols have special meanings, and would not be acceptable. The field for the file name on the REPLOT card is increased from 20 to 45 to permit any Univac acceptable file identifications, ie, it runs from column 11 to column 55. If a subsequent study is started in the same run, this file will be freed (detached from the run) to prevent overwriting of the data.

The procedure described above is an invitation to leave great numbers of catalogued files clogging the system and running up storage charges. Our particular system has no automatic purge procedure. One technique developed to control catalogued files consists of always cataloguing them under a particular project and account number associated with an individual. All files thus catalogued by an individual can then be readily determined and controlled. To use this procedure, if one wished to keep the calculated data for future replotting, one would catalogue a file in a separate run, and then in the job runstream insert cards such as

```
@ASG,AX QUALIFIER*FILENAME.

@USE 4.,QUALIFIER*FILENAME.
```

Note that the ICAT Key must be carefully left zero, or it will trigger the other alternative, freeing this file and cataloguing another file. Also, remember that unit 4 is overwritten by each consecutive study. Consequently, only the data from the last study of a run would be preserved.

EMTP execution on Univac with user-requested program re-dimensioning

When the fixed-size program version available on file U-RHB*LIBS. has proven to be too small for the user's problem, it is readily possible to change the size by execution of a program called VARDIM. It is necessary to determine the tape number on which the program is stored from program maintenance, presently R.H. Brierly, phone 592-4723. The runstream would then be as follows:

1. @RUN as described above.

UNIVAC
UNIVAC
UNIVAC
UNIVAC
UNIVAC

2. @ASG,VT PROG,U9V,NNNNN where NNNNN is the tape number obtained from program maintenance.

3. @ASG,UP A,F///800 Assign a fasten file named 'A'. This particular name is a fixed requirement. Catalogue the file on the assumption that the new-sized program will be used more than once. Local requirements for cataloguing files may require modification of this procedure.

4. @MOVE PROG.,1 Move the tape past the first file which contains the absolute element the same as that available in file U-RHB*LIBS.

5. @COPIN PROG.,TPF$. Read into the user's program file a special compiler, necessary because of the large number of common arrays used in the program. This special compiler may or may not be necessary for the compilation of the subroutines produced by "VARDIM", but it will most certainly be necessary for modification of many of the more complicated subroutines contained in the program. Use of the compiler is obtained by cards of the type "@.FOR,US A.OVER1Z,A.OVER1Z"

6. @COPIN PROG.,A. Read absolute element VARDIM plus all symbolic and relocatable elements of the main program into file A.

7. @XQT A.VARDIM This card, along with the three following data cards, writes a few small subroutines, complete with control cards, on a temporary file logical unit 2.

8.
9.
10. See 0.6 User-Controlled Variable Dimensioning of the EMTP

11. @ADD 2. This card adds the runstream written on logical unit 2 to this runstream, resulting in the compilation of the aforementioned few small subroutines.

12. @PACK A. Prepare file A. for mapping
13. @PREP A.

14. @MAP,N A.TRANSIENTS/MAP,A.TRANSIENTS
This card produces a map (absolute element) on file A. with the N option giving minimum printout.

15. @XQT A.TRANSIENTS Starts program execution.

Individual at Ontario Hydro who is most directly involved with support of the EMTP:

Mr. Russell H. Brierley
Ontario Hydro
700 University Avenue
Toronto, Ontario
CANADA M5G 1X6

Phone: (416) 592-4723

UNIVAC UNIVAC UNIVAC UNIVAC UNIVAC

As indicated on the last page, Russ Brierley remains the principal Univac EMTP contact, and he is the appropriate individual to ask for if telephoning. But if he is unavailable, the caller should be aware that Vladimir (Dr. Vladimir Brandwajn), is also on the same extension. As both an experienced EMTP user and also the incomparable authority on EMTP synchronous machine (S.M.) modeling, Vladimir can also be trusted with any question related to Univac EMTP usage or acquisition. Finally, if neither Vladimir nor Russ are available, and if the caller's question really concerns Univac software as opposed to engineering use of the EMTP, then Ray Boale (spelling?) is the man to talk to. Ray is also located on the 8th floor, I believe (also in Analytical Planning?), though I do not have his phone number immediately available.

The preceding Univac EMTP information dates back to the spring of 1980, while Russ was still working on the "M26." version which was handed over to Vladimir just after Christmas (he was vacationing on the West Coast). The old compiler was used, and dimensioning was restricted so that the natural system limit of 65K decimal words was not exceeded. ALPHANUMERIC variables of the UTPF were translated to INTEGER type in this old scheme, for storage of A6 names.

But with the "M27." version, which was used in Madison at the short course during June of 1980, Russ had a problem. Primarily due to addition of the universal machine (U.M.) modeling of Section 1.63, it was felt that the 65K limit could no longer be lived within for Ontario Hydro studies. On the other hand, breaking out of this barrier with the old compiler was not easy. Russ, Vladimir, and the Oracle (Ray) all struggled with the problem for some time, and collectively decided that a switch to the new Univac ASCII compiler (ANSI FORTRAN, as we understand it in Portland) was the only reasonable solution for the immediate future. This required some additional changes, including the use of REAL*8 (72-bit) variables for the storage of ALPHANUMERIC variables. Well, as of 30 September 1980, Vladimir tells me (by phone) that it is this version which will be given out to others who request the Ontario Hydro Univac EMTP package, since this is the only working version as of today. So, Univac users, beware of the necessity to use the new Univac ASCII compiler, if "M28." EMTP FORTRAN is to be compiled.

In the remaining space, I might provide a more complete address for Russ and Vladimir, as used on our address labels:

Mr. Russell H. Brierley
Dr. Vladimir Brandwajn
Special Studies, Location 8D20
Ontario Hydro
700 University Avenue
Toronto, Ontario M5G 1X6
CANADA

0.5d Honeywell EMTP Setup (as used at Basin Electric in Bismarck, N.D.)

Basin Electric
POWER COOPERATIVE
1717 EAST INTERSTATE AVENUE • BISMARCK, NORTH DAKOTA 58501 • PHONE 701-223-0441 • TWX 910-677-2342

Cataloging and Recovery of Old Plot-Point Data Files

The means by which plot data point files are saved (cataloged) and recovered (attached) differ slightly on the Honeywell system from the procedures used on CDC and outlined in the EMTP manual proper. The following description applies to the Honeywell implementation of these features.

1. Cataloging.

Cataloging will take place if the miscellaneous data parameter ICAT is set to 1 or 2. A catalog entry will be made in the User Master Catalog, immediately upon decoding of ICAT, in the following form:

TPmmddhh.fff

TP = identifying prefix
mm = month
dd = day
hh.fff = current hour and decimal fraction (in hundreths)

This method of file naming ensures uniqueness of identification. (The naming convention has been altered from the standard EMTP form due to a 12-character limitation on file names.)

Since cataloging is performed immediately after decoding 'ICAT', a new file will exist even if the data case aborts (in which case it may well be an empty or 'null' file). The user should keep this in mind so that his permanent-file space usage does not proliferate unnecessarily.

2. Attaching.

The "REPLOT" feature requires the internal attach of a previously cataloged plot-file. The general rules of the EMTP manual section 1.0d apply, except that the file name will appear in columns 11-22 of the "REPLOT" card, and that within this field, embedded blanks and/or separation characters are not allowed. Note also that the "." (in hh.fff) is an essential part of the file name.

Individual at Basin Electric who is most directly involved with support of the EMTP:

Mr. Robert J. Newell
(701) 223-0441 Ext. 211

0.5e Data General EMTP Setup (someday)

During the late winter and spring of 1978, translation details for Data General (DG) were worked out in cooperation with INIE of Lima, Peru. Now that DG has announced its new 32-bit computer system (the Eclipse MV/8000, according to an article in the 5 May 1980 issue of Information Systems News), we would be keenly interested in testing EMTP compatibility with DG . Any potential user who would have interest in setting up a current DG EMTP version should contact Program Maintenance at BPA.

Since space remains, I might present a further report on our DG EMTP considerations. In a letter dated 7 Feb 1978, Mr. Eduardo Zolezzi Chacon, the Subdirector of Mechanical and Electrical Engineering for INIE, first mentioned their DG Eclipse S200 computer. Attached documentation included an IEEE paper (No. A 77 609-1, by Messrs. Gaertner, Morariu, and Zolezzi, entitled "Development and Application of a National Electricity Planning Model") describing the minicomputer support of various system planning programs. INIE had interest in supporting the EMTP in this same way. Subsequent correspondence about details of the translator for DG was with Mr. Fernando Chacon, Head of the Analytic Studies Office of INIE. Except for the possible inability to use REAL*8 storage for ALPHANUMERIC variables of the EMTP, no incompatibilities were spotted; and DG installation-dependent EMTP modules were even punched on cards. But I never received an answer to my letter of 23 May 1978, and the DG translator was never written. The work was suspended. I later learned that both of the aforementioned INIE employees left to work for primvate companies. Today (May, 1980) we have no continuing DG contact with INIE.

That DG S200 computer had 16-bit addressing limits which make its compatibility with the presently-structured EMTP restricted to small problems only. The fixed-dimension S.M. code would probably have to be dropped, etc. If the right contact came along, we might still consider reviving the testing for this machine. But as a general rule, we are forgetting about such address-bound machines, and only worrying about the new architectures. We are definitely interested in benchmarking the MV/8000 ! An analogy can be made between DG and DEC in this respect, with DEC's PDP-11 series being address bound just like the DG S200 . Except for that problem, the DEC VAX-11/780 and the PDP-11/70 are software compatible. Yet no EMTP is running on an 11/70 , despite their frequency of use. My feeling is that the same scenario may well occur for DG , that the EMTP may never be used on the older, address-bound architectures.

Even before the EMTP is available for DG machines, it appears that our interactive CRT plotting program TPPLOT shall be! In a letter from Johannesburg (South Africa) dated 21 Aug 1980, we are informed of plans "to implement the TPPLOT program on a Data General NOVA 3D minicomputer with MEGATEK 5000 refresh graphics terminal. The NOVA is currently linked to our CDC Mainframe on which we (ESCOM) are running EMTP." I approve!

x - f

0.5f PRIME EMTP Setup (as used at MP&L in Duluth, Minnesota)

MINNESOTA POWER & LIGHT COMPANY
30 WEST SUPERIOR STREET, DULUTH, MINNESOTA 55802
PHONE (AREA 218) 722-2641

Program Startup

Assuming the user has performed the normal LOGIN procedure for his installation, execution of EMTP begins by typing in

```
EMTP
```

at command level.

This initiates a small program which in its turn starts the large segmented transients program. A short delay in program response will be experienced by the user during the initial setup. (This is due to the segmented loader paging the program out to disc.)

Execution

The program will request the names of four disc files for input, output, punching, and plotting. The input file must exist in the user's UFD, and all four names must be given regardless of the fact they may not all be used. If the user does not enter a filename as requested, but instead responds with only a carriage return, the program will use its own default names, these being,

```
EMTPIN
EMTPOT
EMTPW1
EMTPPL
```

respectively. After these file names have been entered, the program will begin processing the input data.

Upon successful execution of EMTP, the user's terminal will be returned to normal system command level.

Program Output

To print the output file, type

```
SPOOL  output filename  (F
```

To obtain plots on an electrostatic plotter, type

```
SPOOL  plot filename  (R
```

Individual at MP&L who is most directly involved with support of the EMTP:

Mr. Tom Varilek
(218) 722-2641 ; ask for him by name

PRIME PRIME PRIME PRIME PRIME

0.5g Harris EMTP Setup (as used at the University of Wisconsin in Madison, Wisconsin)

UNIVERSITY OF WISCONSIN-MADISON

DEPARTMENT OF ELECTRICAL
AND COMPUTER ENGINEERING

1425 Johnson Drive
Madison, Wisconsin 53706
Telephone: 608/262-3840

The translation principles for Harris were originally worked out in cooperation with Mr. J. D. Hammerly of the Seattle (Washington) office of Harris. This was using pre-"M21." rules, one of the old translators. When proposals for the BPA EMTP minicomputer were requested, Harris responded with a perfect set of 32 solutions to the standard benchmark problems. This same "M21." program version was sent to Madison for the 1979 EMTP short course, where in June of that year it was used by the 35 or so students who participated.

Well, in the interim the translator has been updated, and in March or 1980 an "M26." translation was mailed to Madison. Fernando is to attempt a setup in preparation for the 1980 EMTP short course. As of April 5, I have heard nothing other than that the tape was received.

Now, in August of 1980, I can add an update. Sang Lee and Fernando quite successfully set up and maintained an "M27." translation for use during the short course. In general, things worked well, though the virtual address space is sorely pressed (Madison has one of those older machines with 18-bit addresses). The Harris EMTP was used exclusively this year (Univac was not employed at all).

Individual in Madison who is most directly involved with support of the EMTP:

Dr. Fernando Alvarado, Professor
(608) 262-8900

Dr. Robert H. Lasseter, Professor
(608) 262-0186

X-h

0.5h Telefunken EMTP Setup (as used at AEG-Telefunken in Frankfurt, West Germany)

AEG-TELEFUNKEN

AEG-TELEFUNKEN E/E2 · Th.-Stern-Kai 1 · D-6000 Frankfurt 70

Energie- und Industrietechnik
Fachbereich
Energieverteilung

Theodor-Stern-Kai 1
D-6000 Frankfurt 70

Telefon: (0611) 600-1
Telex: 4 11 021
Telegramm: elektronzwei

As of the date of writing of this section (April, 1980), it is difficult to say whether AEG-Telefunken will have interest in setting up and checking out a new EMTP version this coming summer. But they certainly have the competence, as documented on page MIUG-15 of the Vol. X EMTP memo dated 8 March 1980 (Ref. 8). I reproduce that description here:

During the spring and summer of 1977, EMTP compatibility problems of the Telefunken TR 440 computer system were worked on with the aid of AEG-TELEFUNKEN of Frankfurt, West Germany. See Vol. IX, 15 July 1979, page VIOE-9, Point 11. The culmination of work here in Portland was a current translation (believed to be "M19.") on 11 August 1977, as documented in my letter of 18 August 1977 to Dr. Dieter Nelles and Mr. B Hartner.

Well, after such a passage of time, we were most surprised and pleased to receive a letter from Frankfurt on 2 April 1980 (letter bears date 27.2.80). The key passage reads as follows:

> "Some weeks ago Mr. Hartner reactivated his EMTP-knowledges and went on to install the program in our system. He had some problems to find a suitable overlay structure because our system linkage editor obviously is not very familiar with programs of such volume. After some minor system/compiler dependent alterations which could not be foreseen in 1977, the first acceptable test results could be run. We have checked now about 70 EMTP test data cases and found differences only in UTPF Test Case No. 17."

By way of explanation, the TR 440 is a virtual machine, and in a letter dated 3 February 1977, I recommended that we ignore the possibility of overlaying for the first try ("Later, after a year or so of experience, you could always add overlaying to the E/T program, should you believe it to be desirable at that time."). So the fact that overlaying had to be added is no real surprise, nor any particular handicap. The Harris virtual operating system Vulcan also requires overlaying to handle the EMTP in Madison (too big, otherwise), and overlaying still seems to be recommended by key IBM users (see Steve Seematter's NPPD experience on page USEC-7 of the Vol. IX EMTP memo dated 10 June 1979). So, no problem here. It sounds like the TR 440 translation has been generally verified, without any help from us here in Portland. Quite an impressive accomplishment, I would say, one which augurs well for our designs of international compatibility.

TELEFUNKEN
TELEFUNKEN
TELEFUNKEN

0.51 Hewlett-Packard EMTP Setup (as Used at Utility X)

The politics of computer acquisition involve some intrigue, and not all parties want all considerations subject to open scrutiny by the general public. So it is with the mystery party which helped develop a translator for H-P 1000-Series machines.

Successful execution can not be reported, since due to reasons which can not be explained here, setup of the program was never seriously pursued. There is no known reason why this discontinued project could not be reactivated, however, if interest appears once again.

I might comment that other H-P minicomputers are not satisfactory replacements for the 1000-Series when it comes to support of the EMTP. Remember, the 1000-Series has that much-advertised capability of addressing two megabytes of MOS memory, directly. Not so for other H-P machines like the 3000-Series, according to our information.

I might also mention that there were compromises and restrictions made, in developing the H-P translator. First, all supporting programs (e.g., "LINE CONSTANTS") were dropped, due to problems with overlaying. Second, fixed-dimensioning was required, due to restriction of that voluminous memory to a single COMMON block. But these were all, and are not so severe as to compromise the project.

For the record, H-P translation procedures were developed during the summer of 1979, with the culmination being an "M24." translation on September 15th, as documented in a letter of mine dated 20 September 1979 . This is current, then. If a 1000-Series owner wants to try again next summer, contact Program Maintenance at BPA. It is in no one's best interest for a project like this to so remain incomplete.

A continuation of this story can now be written during August of 1980. Mr. Nick AbiSamra of Westinghouse in East Pittsburgh expressed interest in shifting the EMTP from their CDC-7600 to their 1000-Series machine. More importantly, he was willing to perform the required testing (of a new "M27." version which we generated for him). Well, as documented in a letter of mine dated August 4th, a couple of serious, even possibly fatal, complications were discovered. Unless these can be resolved, use of 1000-Series machines for support of the EMTP appears to be quite improbable. The local Portland office of H-P was sent a copy of the letter, to see if they had any suggestions for ameliorative action. Very summarily:

1. We need more compiler space, to circumvent "disaster-level" errors associated with table overflow.

2. The passing of EMTP vectors as arguments of subroutine calls is questionable, since $EMA storage is used.

Any readers of this page who have ideas are encouraged to contact us. The 1000-Series would provide most attractive economics, if these technical difficulties can be solved.

0.5j DEC VAX EMTP Setup (as used at BPA in Portland)

A. Background of BPA VAX EMTP

The VAX-11/780 is a fully-virtual 32-bit minicomputer of the Digital Equipment Corporation (Digital; DEC). The operating system is known as VAX/VMS . At BPA, all EMTP work was shifted from our CDC computers to a dedicated VAX in February of 1979 (see Ref. 8, Vol. VIII, 19 November 1978, pagination ABBO). Only manufacturer-documented, standard modifications to VAX/VMS (to increase virtual address space above the standard four magabyte limit) and to the FORTRAN compiler (to allow 300 or so separate labeled COMMON blocks) are in force as of April, 1980, so any other VAX owner should have little difficulty implementing and using the package. Parties interested in acquiring the VAX EMTP materials should direct an inquiry to Drs. W. Scott Meyer and Tsu-huei Liu at the address shown on the front cover.

The interactive plotting program of Section 5.0A is available for VAX users who also have a Tektronix CRT terminal and PLOT10 software. Note carefully that PLOT10 is proprietary with Tektronix, that a user can run the VAX interactive plotting program in the vector-graphic mode without alteration only if he has purchased the PLOT10 package from Tektronix. Instructions for the use of interactive plotting will be found in Ref. 8, Vol. IX, 11 May 1979, pagination PIEP.

A similar statement applies to CalComp or simulated-CalComp output of either the EMTP or the interactive plotting program. Only if the user has purchased a CalComp or CalComp-like plotting capability (BPA uses an 11-inch Versatek printer/plotter) can CalComp plotting be utilized.

Although not in place as of March, 1980, the DEC software for network communication among two or more VAX computers has been ordered. This is DECnet, which will provide us with direct, high-level telephone communication with other VAX installations. This should prove very handy for the exchange of small files among VAX EMTP users in North America.

B. Content of Standard VAX EMTP Tape

Requests for the VAX EMTP should be mailed to Program Maintenance at BPA, and should be accompanied by a reel of magnetic tape. For the full package (including the files of Section E), a full 2400 feet of tape are required as of April, 1980. Just EMTPNEW.EXE , interactive plotting, and TPEDIT can be put on very little tape (200 or 300 feet); if just this partial package is desired, please send a small reel of tape (for ease of mailing). Well, once we have the tape in hand, disk files are then copied onto the user's tape using the BPA DEC TE16 tape drive. The format shall be 9-track, 1600-BPI (800 could be arranged if needed, by special request), labeled with "EMTP" ($ INIT EMTP), and created using VAX/VMS $COPY commands. The following files will always be sent, and should be of interest to the average user. This is a basic minimum set:

[UT]EMTPNEW.EXE;1 ----	The executable image of the current production version of the EMTP. Dimensioning is enormous (/LABEL/ size is over 3/4 MB). Do not try to use CalComp EMTP plotting.
[TSU]NEWMODS.OBJ;1 ---	Compiled output of the variable-dimensioning program VARDIM. Dimensions correspond to those of EMTPNEW.EXE .
[TSU]VARDIM.EXE;1 ---	Executable image of the variable-dimensioning program.
[SCOTT]TPPLOTKOM.FOR --- [SCOTT]TPPLOT.*	Interactive CRT plotting program. The first file is referenced by INCLUDE usage of TPPLOT.FOR . A user having a Tektronix vector-graphic terminal must compile and link this FORTRAN with his own Tektronix PLOT10 package.
[UTPF]OVM1.OBJ;1 [UTPF]OV0.OBJ;1 [UTPF]OV1.OBJ;1 : Etc. [UTPF]OV55.OBJ;1	Overlay object files of the EMTP. When linked together with NEWMODS and the user's CalComp plotting modules, a CalComp-plotable, executable EMTP image results. In linking, NEWMODS must be first.
[SCOTT]TPEDIT.* -----	Interactive editing program that was designed especially for EMTP output files. Great for saving paper! See Ref. 8, Vol. X, 13 January 1980 , pagination TEFE.

It is possible that many hundreds of additional files shall also be on the VAX EMTP tape. Notice that the above listing makes no mention of standard test cases, or of the EMTP FORTRAN. But because such files need not concern the average VAX EMTP user, further consideration has been postponed until Section E.

C. Common Usage of VAX EMTP Materials

Basic execution procedures

EMTP execution is normally done on the VAX via a command procedure file such as GOEMTP.COM which follows:

```
$ ASSIGN  EMTPDATA.DAT  FOR005
$ ASSIGN  PRINTOUT.LIS  FOR006
$ SET WORKING/LIMIT=350
$ RUN/NODEBUG  [UT]EMTPNEW.EXE;1
```

It is here assumed that the data case (or cases) to be solved has been stored on disk as a file named EMTPDATA . The EMTP printout goes on disk, too, as a file named PRINTOUT . Should a printed copy of the output file be wanted, the command `$ PRINT/DELETE PRINTOUT` will do the job (and destroy the file when completed). Alternatively, the user may be operating remotely through a terminal, and he may want to take a look at the output file using the VAX interactive text editor SOS, before any final disposition is to be made. In this case, `$ EDIT PRINTOUT.LIS` is all that it takes. There also is a special EMTP output-file editor TPEDIT (described in Ref. 8, Vol. X, 13 Jan 1980, pagination TEFE), which is handy for serious production users. All of these options for handling the output file are possible because of the ASSIGNment of a disk file to FOR006 .

There still is the choice between the interactive and batch modes of execution:

a) The command `$@GOEMTP` will result in interactive execution. Often, the `$ ASSIGN PRINTOUT.LIS` command would be omitted in this case, so that output would be written to the terminal as it is generated. This mode is very useful, provided the volume of output is not excessive, and provided the terminal is driven at sufficient speed (all in-house BPA CRT terminals run at 9600 baud). But such usage can be quite unsatisfactory for slow typewriter terminals (e.g., our own 30 character per second DECwriter console). If a CRT is used, then no permanent copy of the EMTP output is preserved, unfortunately (once it rolls off the top of the screen of a dumb terminal, it is gone forever). A final disadvantage is that the terminal is tied up during the interactive execution.

b) The command `$ SUBMIT GOEMTP` will result in the queueing of the command procedure for batch-mode solution. This is the basic form of the command, with variations possible based on local decisions as to priorities, resources, etc. VAX/VMS will respond with some acknowledgement like "Job 287 entered on queue SYS$BATCH" . At this point the terminal is free, and the job is out of the user's hands. Most production EMTP studies (Al Legate and Bob Hasibar) are so executed. A file should always be assigned to unit 6 in this case (otherwise, output goes to the default file FOR006.DAT).

VAX

Such discussion of DCL (Digital Command Language) usage could go on and on, of course. Very powerful and flexible things are possible, though they are beyond the scope of the present discussion. The voluminous "VAX-11 USER; Student Guide; Student Workbook" produced by DEC is an excellent motivator for the innovative use of the system. Less tutorial, but also good, is the DEC "VAX/VMS Command Language User's Guide." Most basic of all, and the simplest to read, is the DEC "VAX/VMS Primer." All of this material is available through DEC, and not BPA.

Because production versions are compiled and linked with the interactive debugger on, the "/NODEBUG" qualifier is required on the execution request, to bypass such usage. But if this very powerful diagnostic tool is wanted, consult the DEC "VAX-11 Symbolic Debugger Reference Manual". The only special EMTP caution is that execution of the debugger begin with CANCEL MODULE MAIN10 ; this gains extra working space, if a big module is to be investigated.

Plotting of VAX EMTP solutions

Plotting with the VAX EMTP is easy. The "PRINTER PLOT" feature of course always works, and shall not be mentioned further. Quality EMTP plotting (so-called CalComp plotting) requires that the user link the EMTP along with his CalComp plotting modules LINE, GRID, SYMBOL, etc. Interactive plotting TPPLOT will produce line-printer type plots for anyone, using any terminal. But for vector-graphic plotting on Tektronix terminals, interactive plotting must be linked along with the user's PLOT10 package. Saving of the plot file after an EMTP solution is done automatically, if miscellaneous data parameter "ICAT" has value one or two. The form of the plot file name that results is MDDHHMMSS.PL4 , where "PL4" is simply a characteristic file type, and "MDDHHMMSS" are digits of the date and the time. The "M" is a hexadecimal digit for the month (with "A" for October, "B" for November, and "C" for December). Files are created in the directory of the user, so can be spotted using $ DIRECTORY *.PL4 .

As for the "REPLOT" feature of Section 1.0d, this requires a special format (do not try to use that shown) which is as follows: "REPLOT, FILE, IPRSUP" . This is free-format after the key word "REPLOT" (which must begin in column 1), so blanks can otherwise be interspersed at will. The commas (",") are the familiar free-format field separators. Field FILE must be a legal VAX file specification (e.g., [TSU]A17234105.PL4) of 25 or fewer characters, and IPRSUP is an integer constant used for diagnostic printout control.

Usage of "TABULATE ENERGIZATION RESULTS"

As for the use of "TABULATE ENERGIZATION RESULTS" of Section 1.0e6 (or alternatively, use of "STATISTICS OUTPUT SALVAGE" of Section 1.0e7), there are two disk files for each "STATISTICS" data case that was solved and saved:

```
ST3LOG???.DAT --- file for  LUNIT3 = 3  file ;
ST9LOG???.DAT --- file for  LUNIT9 = 9  file .
```

Here "???" are the three decimal digits that are uniquely associated with the file (see "JFLSOS" in Section 1.0e7). These files are opened without directory specification or version number, so must be in the user's area, and will always be the highest version (if more than one having the same name exists). In the case of "TABULATE ENERGIZATION RESULTS" usage, there will be confirmation of the connection of each disk file in "STATRS" of overlay 29 ---- one at a time, as the attachment is made. These go in pairs, the ST3 file following the ST9, for each of the previously-solved "STATISTICS" cases. The opening and confirmation for the file of LUNIT9 are performed as follows:

```
         OPEN (UNIT=1, TYPE='OLD',NAME=FILN20,FORM='UNFORMATTED')
         WRITE (LUNIT6, 1822) FILNAM
    1822 FORMAT ( 20X,
       1   '----  SUCCESSFUL  OPEN  OF  'LUNIT9'  DATA ON'
       2   ' DISK.   PERMANENT FILE NAME =',  3H  ',  20A1,
       3   3h' .   )
```

If there is a job bomboff (system interrupt) before all such printouts are seen, presumably the file following the last one printed could not be found on disk by VAX/VMX . Files are taken up in the order of user input, from left to right on each data card. As for the creation of such files in the first place (the preceding "STATISTICS" simulations), file opening is done in "MIDOV1" of overlay 1, without any version number. Hence there is no fundamental problem with using the same characteristic integer "JFLSOS" more than once, since higher versions will simply be created. However, if any other than the highest version is wanted for tabulation, renaming will be necessary (since the attaching of "STATRS" is done without version number).

Allocation of physical memory

The allocation of physical memory (350 pages in above example, via $ SET WORKING) will depend on the size of the data case being solved. A figure of 350 pages works well for most production BPA cases, avoiding paging in the time-step loop. But much larger cases have been solved using less memory (see Ref. 8, Vol. IX, 10 June 1979, page USEC-9); there simply is substantial paging, and execution is slowed. The user can and should experiment with this, if memory is not abundant.

Use of MEMSAV = 1 and "START AGAIN" Features

The integer miscellaneous data parameter MEMSAV (see Section 1.0h), when set to unity, will result in a dumping of EMTP memory onto disk at the conclusion of a simulation. The "START AGAIN" request of Section 1.0e15 can then subsequently be used to restart such a halted run. But there are some VAX-dependent aspects to be considered.

First, there is the "file specification" of the "START AGAIN" card. This will be seen by looking at the special line of printout which precedes the extrema:

```
   ----- SUCCESSFUL SAVING OF  /BLANK/  AND  /LABEL/  AS
   DISK FILE  "TPTABLES.BIN" .   N1, LTLABL =    1352  225779
```

Thus the file name is TPTABLES.BIN , in the user's directory, and without version number. Each time memory is so saved, a higher version is created. As for N1 and LTLABL , these are sizes of /BLANK/ and /LABEL/ , respectively, in INTEGER*4 words. The latter (LTLABL) is determined completely by the user's variable dimensioning, while the former (N1) may vary with program version (e.g., "M28." and "M29." versions may or may not be compatible for such usage, even if EMTP list sizes are identical).

A user of the MEMSAV = 1 option should monitor his available disk space closely. First, TPTABLES.BIN is a big file, with my test on 04-JUL-80 showing 1832 blocks (938 Kbytes) in response to a $DIRECTORY TPTABLES.BIN command. The overhead is thus substantial, if disk is in short supply, using our enormously-dimensioned BPA image. This could be drastically decreased if the user cut EMTP table sizes, but then one would have to worry about saving the corresponding EMTP version, which is an even bigger file (5765 blocks for "M27.+"). The best general strategy is believed to be use of one enormously-sized executable image of the EMTP.

Treatment of EMTP free-format using VAX

EMTP free-format is treated in Section 0.7 . Note that there is mention of possible problems with precision on some computer systems, due to roundoff-like error involved with use of the FORTRAN "**" operation. VAX was one system with this problem (sometimes only 8 or so digits of significance were achieved, though computation is all IMPLICITEly REAL*8). Well, the solution was to write module FRENUM that is called by a near-universal FREFLD . Module FRENUM writes the characters of the next free-field number on FOR039 , and then reads them back using DEC free-format : READ (39, *) D1 . Hence if there is still a precision problem, it is DEC's fault!

D. $-Cards for VAX EMTP

So-called $-cards were introduced in Section 1.-D, and it is assumed that the user has read that material before continuing with what follows. Concerning format rules, remember that the "$" and following request word must be a continuous string of characters (with no imbedded blanks). Thereafter, EMTP

1

X-25

free-format is us_d, so blanks are acceptable anywhere (see Section 1.0gb). Well, the following S-cards are honored by the VAX EMTP :

1. SATTACH, FILE, M

This command serves to connect a disk file having name FILE (any legal VAX file specification of not more than 25 nonblank characters) to EMTP I/O unit number M (an integer constant). The EMTP data card interpetation involves the printing of FILE and M : "ATTACH FILE: $\boxed{\text{25A1}}$ UNIT = $\boxed{\text{I3}}$ "

If I/O unit number M is blank or zero, the EMTP will simply connect the disk file to that free channel which has the lowest unit number (e.g., if unit 1 is free, it will be used). Whatever was connected to I/O channel M before the new connection is first released (CLOSE operation).

Sample usage: "SATTACH, [TSU]NED96.DAT;1 , 4"

2. SPUNCH, M

This command serves to copy the 80-column card image contents of EMTP I/O unit number M (an integer constant) to the card punch. The only problem is that I have yet to find a VAX owner with a card punch! VAX FORTRAN does not honor the CDC output command "PUNCH" , either. Cards are going the way of the dinasaur in this business, anyway. So, doing the best I could, I simply copy the card images to unit 7 (FOR007). Data card interpretation involves the printing of M :

"COPY FILE $\boxed{\text{I4}}$ TO PUNCH ."

The contents of unit M are rewound before and after the copy operation; the unit 7 file is not, of course.

Sample usage: "SPUNCH, 9"

3. SOUTPUT, M

This command serves to copy the 80-column card-image contents or EMTP I/O unit number M (an integer constant) to the line printer (the FOR006 connection). If M is zero or blank, a value of 7 is assumed (the card-punch file). EMTP interpretation of the data card involves the printing of M :

"COPY FILE $\boxed{\text{I4}}$ TO OUTPUT ."

The contents of unit M are rewound before and after the copy. As for the line printer file (FOR006), records are printed single-spaced, with the following identification, beginning in column 20 of the paper:

"RECORD $\boxed{\text{I5}}$. 1 $\boxed{\text{10A8}}$ "

The I5 field is for the record number (1, 2, etc.), while the "1" to the left of the card image serves to identify the left margin of that image (it is a column-zero marking).

Sample usage: "$OUTPUT, 9"

4. SSAVE, FILE, M, N

This command serves to copy the 80-column card-image contents of EMTP I/O channel number N (an integer constant) to I/O channel number M (an integer constant), and save the result as a new disk file named FILE (any legal VAX file specification having not over 25 non-blank characters). Data card interpretation involves the printing of FILE and M :

"SAVED FILE: $\boxed{\text{25A1}}$ UNIT = $\boxed{\text{I3}}$ "

X

VAX

VAX

VAX

VAX

VAX

VAX

The contents of unit N are rewound before and after the copy operation, and the newly-created file is disconnected from unit M (CLOSE command) after it has been completed.

If N is zero or blank, it is assumed that the user wants to save a copy of the unit 7 (FOR007) punch file. But do not forget the comma preceding N , ever. If M is zero or blank, the EMTP will simply use that free I/O channel which has the lowest number for creation of the new disk file.

Sample usage: "$SAVE, [SCOTT]NEWFILE.DAT, 1, 9"

5. $INCLUDE, FILE, M

This command serves to insert the data of disk file FILE (any legal VAX file specification having not more than 25 non-blank characters) into the EMTP data-input stream at this point. Functionally, this corresponds to the INCLUDE function of VAX FORTRAN, though here we are concerned with EMTP data rather than computer code. An extra I/O channel number M (an integer constant) is required for temporarily connecting FILE to the EMTP. Records are read until an end-of-file is encountered, at which point input reverts to the original input unit. Such usage can not be nested (the contents of FILE must not contain $-INCLUDE usage themselves: one is not allowed to have an INCLUDE inside an INCLUDE). The data card interpretation involves the printing of FILE and M :

"INPUT FILE: $\boxed{25A1}$ UNIT = $\boxed{I3}$"

If M is zero or blank (but remember not to omit the preceding comma separator), the EMTP will simply use that fre I/O channel which has the lowest number for connecting the file in question.

Sample usage: "$INCLUDE, [BOB]HEAVY.DAT;37 , 0"

6. $DISABLE

This command marks the beginning of the implicit commenting of a block of data cards; it "disables" the following EMTP data cards. There are no parameters, and the card is universal (can be implemented on any computer system). Interpretation of this data card will be:

"BEGIN DATA TO BE IGNORED."

This implicit commenting then remains in effect until it is ended by a following $ENABLE card (see Number 7).

7. $ENABLE

This command marks the ending of the implicit commenting of a block of data cards; it cancels the action of a preceding $DISABLE card. There are no parameters, and the card is universal (can be implemented on any computer system). Interpretation of this data card will be:

"END OF DATA TO BE IGNORED."

8. $RETURN, M

This command serves to disconnect (CLOSE) the data file that is connected to EMTP I/O channel number M (an integer constant). Data card interpretation involves the printing of M :

"CLOSE FILE ON UNIT $\boxed{I3}$."

If M is zero or blank (but remember not to omit the preceding comma separator), I/O channel LUNIT4 = 4 , the file of raw plot data points, is assumed.

9. $NEWFILE, FILE, M

This command serves to connect EMTP I/O channel number M (an integer constant) to a brand new disk file named FILE (any legal VAX file specification having 25 or fewer nonblank characters). This is in preparation for EMTP-generated, UNFORMATTED data to subsequently be written to the file via the I/O channel M . After such file-filling is complete, $RETURN can be used to disconnect the newly-created file from I/O channel M . Data card interpretation involves the printing of FILE and M :

"NEWFIL FILE: $\boxed{\text{25A1}}$ UNIT = $\boxed{\text{I3}}$ "

If M is zero or blank (but do not forget the preceding comma separator), M = 4 is assumed (corresponding to the file of raw plot data points).

Note the restriction to UNFORMATTED files; card-image copies to the file is not allowed. If a corresponding $-card for FORMATTED usage is desired, we can create it easily enough (call Program Maintenance at BPA). Present thinking is that usage will probably be just for the plot file, which does involve only UNFORMATTED writes. Unfortunately, VAX/VMS forces the user to declare beforehand his choice between these two modes, which is why there is the UNFORMATTED restriction.

Sample usage: "$NEWFILE, [AL]PLOTFILE.PL4, 0"

10. $DIAGNOSTIC, IPRSUP

This command serves to redefine the diagnostic printout control parameter IPRSUP (an integer constant) within the overlay where the data card is being read. But when a new EMTP overlay is entered, the effect is lost. This $-card is universal in that it can be implemented on any computer system. As for the value of IPRSUP , see Section 1.0h, the integer miscellaneous data card (which carries the same parameter). Read also the universal comments of Section 1.-D . Interpretation of this data card involves the printout of IPRSUP :

"NEW IPRSUP = $\boxed{\text{I4}}$ "

Sample usage: "$DIAGNOSTIC, 9"

11. $DELETE, FILE, M

This command serves to destroy an arbitrary disk file named FILE (any legal VAX file specification having 25 or fewer non-blank characters). I/O channel number M is simply a free channel to temporarily be used during the destruction process. Data card interpretation involves the printing of FILE and M :

"DELETE FILE: $\boxed{\text{25A1}}$ UNIT = $\boxed{\text{I3}}$ "

If M is zero or blank (but do not forget the preceding comma separator), the EMTP will simply use that free I/O channel which has the lowest number.

Sample usage: "$DELETE, [BOB]BYEBYE.BYE;*, 0"

12. $MONITOR, TEXT

This command serves to provide a line of CRT output at the instant the data card is read, for interactive EMTP execution, It has meaning and practical use if the output file of FOR006 (unit LUNIT6 = 6) is assigned to a disk file. Then, in the absence of a $MONITOR card, there would be no terminal output as execution proceeds (until the STOP of "SUBR31" is reached, when "FORTRAN STOP" is written to the terminal by VAX/VMS). Using $MONITOR , the user can be periodically reassured of the progress of data input.

When the $MONITOR card is read by the EMTP, the card image will show up in the output file of FOR006, but without any column 1-50 interpretation. The same card image is written to the terminal, and will there be interpreted with printout which includes the data card number NUMDCD :

"CRT MONITOR, CARD NUMBER = $\boxed{I5}$ "

Here NUMDCD is simply a cumulative count of the number of input records, which provides the user with a measure of positioning. If on the other hand unit 6 is not assigned to a disk file, then two card images will be seen to the right of column 51, with only the second one being so interpreted (the first will have columns 1-50 blank). As for what happens in the case of batch-mode solution, I have yet to try it. In any case, PRINT is used.

The parameter TEXT is arbitrary, and can be punched with whatever identifying information the user wants. Since $MONITOR, requires nine columns, 71 remain for TEXT (which is not actually processed by the EMTP).

Sample usage: "$MONITOR, END OF EMTP BRANCH DATA."

13. $LISTOFF

This command serves to turn off the interpreted listing of input data cards, beginning with the card which immediately follows. This $-card is universal in that it can be implemented on any computer system. It is nullified by a subsequent appearance of $LISTON (see Number 14 below). Interpretation involves printout of the cumulative data card number NUMDCD :

"TURN OFF INPUT LISTING AT CARD $\boxed{I5}$ "

Common usage of this feature is to save paper (particularly for users of slow peripherals, like 300-baud typewriters) during the data-input phases of the program. But the user should be aware that more that just the data-card listing can be so shut off. In fact, all production printout (including the data-card listing) is affected. This is because the printout control variable NOUTPR , which was originally added to suppress all output during a MODIFY DELTAT restart, is used by $LISTOFF . Hence do not leave $LISTOFF in effect beyond the last source card, if such additional suppression is to be avoided.

14. $LISTON

This command serves to cancel a preceding $LISTOFF request (see Number 13), which turned off the output. The $LISTON command turns the output back on again. It is universal in that it can be implemented on any computer system. Interpretation involves printout of the cumulative data card number NUMDCD :

"TURN ON INPUT LISTING AT CARD $\boxed{I5}$ "

X-j8a

15. $VINTAGE, M

This command serves to redefine the vintage number of data formats which are to be used (where two or more choices are available, it is the vintage number which selects between them). The $-card is universal (can be implemented on any computer). Data card interpretation involves the printing of M , which is the new data vintage number:

"NEW MOLDAT = $\boxed{\text{I4}}$ (DATA VINTAGE)"

16. $OLDFILE, FILE, M

This command is identical to that of Number 1 ($ATTACH), except that it applies to UNFORMATTED files (e.g., plot files of LUNIT4) rather than FORMATTED ones. Also, the data card interpretation is different, using the characteristic identifier "OLDFIL" rather than "ATTACH" .

The $OLDFILE command was actually implemented for usage with postprocessing of old plot files using TACS, as described in Section 1.0e17 . For this usage, remember that VAX plot files names are of the form MDDHHMMSS.PL4 , and that I/O unit LUNIT19= 19. Thus sample usage would appear as follows for a file created on October 13th at 23:41 and 52 seconds:

```
$OLDFILE, A13234152.PL4, 19
```

17. $STOP

This command serves to terminate execution of the EMTP immediately, locally (within "CIMAGE"). This $-card is universal in that it can be implemented on any computer system. Interpretation is as follows:

"STOP EXECUTION IMMEDIATELY, IN 'CIMAGE'."

Needless to say, the $STOP card has no application to normal production usage; it is designed only for test purposes by Program Maintenance, who may desire to terminate execution at a certain point in the data input.

18. $WATCH5, M

This command serves to direct 72-column input card images to be written on the screen as they are read by the EMTP, every M-th card. This normally will only be used for interactive execution of the EMTP through a terminal, with FOR006 assigned to a disk file. Otherwise there would be no output on the screen as the case executed; this way the user can at least monitor the input data as it is being read. Interpretation of this request record involves the printing of M :

"PAINT INPUT DATA ON SCREEN. $\boxed{\text{I8}}$ "

As for values of parameter M , zero or blank (but do not forget the preceding comma separator) is equivalent to unity, resulting in the writing of each data record to the terminal (CRT screen). To later stop such extra output, simply use a large positive value for M .

Those EMTP data cards which are written to the terminal via this request are slightly truncated:

```
          PRINT 3009, NUMDCD, (ABUFF(I), I=1, 9)
     3009 FORMAT ( 1X, I5, 2H :, 9A8 )
```

Integer NUMDCD is the data card number.

VAX VAX VAX VAX VAX VAX

E. VAX EMTP FORTRAN and its Modification

For those who want to alter the VAX EMTP FORTRAN, all supporting programs and files which are associated with our minor-update procedure may also be copied onto the user's tape. In fact, the user may get such files even if he does not want them, in the name of uniformity and completeness! Documentation is to be found in various memos of Ref. 6, Vol. IX, 28 May 1979 through 5 August 1979. In all file names shown below, the star ("*") is the VAX/VMX "wild card", meaning that any legal string of characters for that portion of the specification is accepted. The added files that are copied to the user's tape from our BPA disk using GIVEAWAY.COM are:

[UTPF]*.SPL;66	--------	Segments of the production UTPF. There were 236 of these in the "M26." version of 26 December 1979 . A list of all segments is found in the exceptional file named UTPFPARTS.SPL;66 (use $TYPE or $PRINT to look at it).
[UTPF]*.FOR;1	---------	The INCLUDE files of the EMTP FORTRAN (which is not on the tape). Exception is the file VARDIM.FOR , the variable-dimensioning program FORTRAN.
[SCOTT]TPUPDATE.*	----	The program which generates DCL for the minor-update. The executable image ".EXE" is run by MINORMUP.COM . Both ".FOR" and ".EXE" files should be picked up by the wild card copy.
[TSU]EMTPDECK.FOR;1	---	Structure file showing modules, decks, and where the latter are called by the former. To display this, use $TYPE .
[SCOTT]VAXET22.* [SCOTT]VAXETKOM.FOR	----	VAX E/T (translator) files. The second file is an INCLUDE file of VAXET22.FOR . Both ".FOR" and ".EXE" files should be picked up by the wild card copy.
[TSU]MINORMUP.COM	----	File of DCL to actually perform a minor update. See pages VIUE-14 through 19 of Vol. IX EMTP memo dated 15 July 1979 .

[TSU]LISTSIZES.DAT;1 --- Data to be read from unit 5 when the variable-dimensioning program is executed. Four 80-column card images of List sizes for the EMTP are present.

[UTPF]*.OBJ;1 --------- Individual object files of each EMTP SUBROUTINE or FUNCTION module. An exception is VARDIM.OBJ , the compiled variable-dimensioning program. Also carried along by a wild card copy are the overlay object files OVM1 through OV55 which were described in Section 8.

[SCOTT]GENCOR.* ----- Program to generate correction records corresponding to program changes. Both ".FOR" and ".EXE" files are carried by the wild-card copy. See Ref. 8, Vol. IX, pages GENC-1 and CRTP-5 .

[SCOTT]ADDCOR.* ------- Program to merge two or more sets of UTPF correction files (as produced by GENCOR). Both ".FOR" and ".EXE" files are carried by the wild-card copy. See Ref. 8, Vol. IX, pages GENC-5 and CRTP-1 .

[SCOTT]USECOR.* ------- Program to apply corrections-record files to the production UTPF, to re-produce modified UTPF segments (the reverse of GENCOR). Both ".FOR" and ".EXE" files are carried by the wild-card copy. See Ref. 8, Vol. IX, page CRTP-8 .

[SCOTT]LISTMAKER.* --- Program which creates a list of UTPF segments that must be processed. Both ".FOR" and ".EXE" files are carried by the wild-card copy. See Ref. 8, Vol. IX, page CRTP-6 .

[SCOTT]FORTOUTPF.*
[SCOTT]UTPFTOFOR.* --- Programs which shift card-image files by eight columns on the left, corresponding to the difference between FORTRAN and VAX UTPF formats. The first one adds eight blanks to the left side of a FORTRAN file (mnemonically, FORTRAN to UTPF), while the 2nd program strips off eight such

x-j11

characters from the left edge of a VAX UTPF file (mnemonically, UTPF to FORTRAN), giving FORTRAN. Both the ".FOR" and ".EXE" files are carried by the wild-card copy. See Ref. 8, Vol. IX, page VIOE-4 . VAX

[SCOTT]LISCOR.* ------ Program to list a set of UTPF correction-file segments in quality fashion. Both the ".FOR" and ".EXE" files are carried by the wild-card copy. See Ref. 8, Vol. IX, page VIOE-19 . VAX

[SCOTT]CUTUTPF.* ------ Program to convert between a a single-file, universal-format UTPF and the segmented, transposed (icent on left) format used on the VAX. Both the ".FOR" and ".EXE" files are carried by the wild-card copy. See Ref. 8, Vol. IX, pages SOTU-3 and MMIO-13 . VAX

[SCOTT]PACKUTPFT.COM --- Command procedure that is used to create a single-file, universal-format UTPF. It runs CUTUTPF. See Ref. 8, Vol. IX, page MMIO-13 . VAX

While in no way intending to repeat much of the existing Vol. IX material, an overall summary of the use of these files shall be provided:

S1. All files of directory [UTPF] are locked to the average user, as are [UT] files; the average user has read-only privileges, to protect the contents. A user intending to alter one or more UTPF segments copies from [UTPF] to [TSU] , changing the file type to ".MUP" in the process. VAX

S2. Using SOS, a user then makes any coding changes to such copied UTPF segments. Columns 1-8 (the UTPF ident) is to be blanked out for any altered (or added) record. This is the identifying property which GENCOR relies on, so the rule must be scrupulously adhered to. The blanking out of columns 1-8 is trivial and automated, using ALT-mode of SOS (with the line in question being the current line, send "A" first, then the ten characters "8C   "). VAX

S3. When the editing of a UTPF segment is completed, SOS should be exited in a way that kills page marks and line numbers (use "ET" or "EBT"). If this is not done, programs (e.g., the translator) which read the files will stumble after record number 655 of such a segment, and the tail end of such a file will be lost (which may only be spotted later, during compilation, with error messages about a missing END statement and missing statement numbers).

S4. Actually performing the minor-update is trivial : $@MINORMUP . Usually performed interactively, the user can monitor every stage of the process, even on slow typewriter terminals. If the job is successful (no FORTRAN errors, etc.), the result will be a new executable image named [TSU]EMTPMUP.EXE;1 . If the process should be aborted by the user after one or more overlay object files have been created, be sure to manually delete these before attempting another minor update. For example, if overlay 15 compilation and copying was completed, send a $ DELETE MV13.OBJ;* to remove the problem file..

S5. If a separate file of FORTRAN is to be inserted into the EMTP at some point, first process this file using FORTOUTPF.EXE so as to add eight blank columns to the left of each card image. Then use the SOS copy-command "*C" to insert the result into the appropriate UTPF segment at the desired point.

S6. To extract UTPF-correction records from the modified UTPF segments [TSU]*.MUP , execute GENCOR.COM (which internally runs GENCOR.EXE). The resultant correction files can then be communicated to Program Maintenance at BPA, should this be desired (i.e., this is the level at which VAX users exchange program changes to the current production version). In order to list the correction files in high-level, readable form, execute LISCOR.COM .

F. VAX EMTP Test Cases

At the time of writing of this section (March, 1980), it is difficult to predict the final form of VAX EMTP test case materials. I would point out the structural work using TPEDIT , as documented in Ref. 8, Vol. X, 13 Jan 1980 , pages TEFE-5 through 10 . Unless the preliminary design is changed, the data cases will all be copied onto the tape as [TEST]*.DAT . The BPA VAX EMTP solutions would then be the corresponding files [TEST]*.LIS . Whether only a limit set of 32 or so will be supplied, or a full set of about 170, will depend on available time and later decisions. I personally do not see test cases as much of an issue with the VAX EMTP, since most recipients will simply use EMTPNEW.EXE without any testing or thought about possible complications.

G. Temporary VAX/VMS Trouble Copying Overlay Object Files

As of March, 1980, there is a VAX/VMS complication related to overlay object files. Two overlays never seem to make it from disk to tape, as per the following system error messages:

```
$ COPY  [UTPF]*.OBJ;1          TAPE
%COPY-E-READERR, error reading SIA0:[UTPF]OV31.OBJ;1
-RMS-W-RTB, 255 byte record too big for user's buffer
%COPY-W-NOTCMPLT, SIA0:[UTPF]OV31.OBJ;1 not completely copied
%COPY-E-READERR, error reading SIA0:[UTPF]OV43.OBJ;1
-RMS-W-RTB, 256 byte record too big for user's buffer
%COPY-W-NOTCMPLT, SIA0:[UTPF]OV43.OBJ;1 not completely copied
$ COPY  [UTPF]*.SPL;66         TAPE
```

Until this problem is corrected (we are open to suggestions; no one Terry has talked with knows anything about it), a user who wants to employ the overlay object files must re-create two of them on his own. The easiest way is to perform a minor-update (see MINORMUP.COM file) that involves just these two overlays, aborting the job using CTRL-Y once linking begins. Rename the files MV31.OBJ;1 and MV43.OBJ;1 as the missing overlay object files [UTPF]OV31.OBJ;1 and [UTPF]OV43.OBJ;1 . As for which UTPF segments to modify by making no changes, pick short ones (for fast compilation) like OVER31 and OVER43 .

Until this VAX/VMS copying problem is resolved, note that the overlay object files by themselves (without the individual module object files) are of no value. The abbreviated tape contents of Section B must be further abbreviated to just EMTPNEW.EXE , the interactive plotting files, and TPEDIT , then. For this, a really small reel of tape (250 or 300 feet) should suffice, at 1600 BPI.

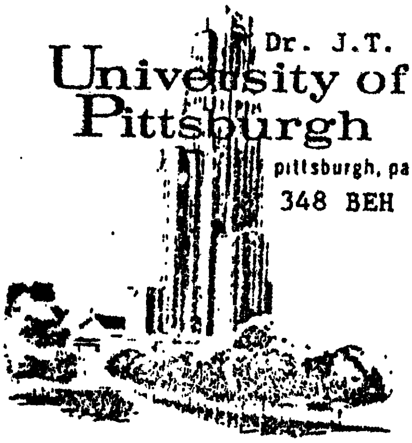
H. Required Virtual Address Space for EMTP Execution

At the beginning of the VAX section, an allusion was made to the need for more than four megabytes of virtual address space, in order to execute the EMTP. But how much? This is not a static figure, and may be expected to grow along with the program. As of the summer of 1980, we at BPA are continuing to live within an eight megabyte limit. But perhaps this will have to be raised in time, too (we started with the "421." code on the VAX, using the standard four megabyte limit).

51

X-K

0.5K DEC PDP-10 EMTP Setup (as used at University of Pittsburgh)


Dr. J.T. Cain
University of Pittsburgh
pittsburgh, pa. 15261
348 BEH

1787
SCHOOL OF ENGINEERING
UNIVERSITY OF PITTSBURGH
PITTSBURGH, PENNSYLVANIA 15261

DEPARTMENT OF ELECTRICAL ENGINEERING

The PDP-10 is Digital Equipment Corporation's original 36-bit word machine. It thus is quite distinct from the VAX-11/780 as used at BPA (see Section 0.53). The newer DEC word machine SYSTEM20 can also be handled by the PDP-10 version, since these two machines are software compatible.

The "M21." PDP-10 translator was developed in cooperation with Dr. J. Tom Cain, Professor of Electrical Engineering at the University of Pittsburgh in Pittsburgh, Pennsylvania. This was for an "M21." version. Tom successfully set up the translation which we mailed him, and has supplied it to a few other interested parties (including Lawrence Livermore Laboratory).

So, the EMTP was fully operational on the PDP-10 as of "M21." versions. But the translator has not yet been upgraded past the "M22." discontinuity, and no committments to handle a new program version during the summer of 1980 have yet been discussed.

Tom's reaction to a photocopy of the preceding material is contained in a letter to me dated 30 April 1980 . First, he confirms my largely-undocumented impression that the "M21." PDP-10 version is generally working:

> "I believe that the statment 'EMTP is fully operational on the PDP-10 as of M21' can be made with at least 99% confidence. I have had several students use EMTP as part of their work and they have exercised enough of the program that I believe all other parts should work properly."

I mention this not because it has any lasting importance in and of itself; it does not (the "M21." version will be dated by July or August of 1980). Rather, it is important as a verification that PDP-10 system software seems to be compatible with the EMTP. As much as any other computer which has not had newer versions tested , the PDP-10 appears capable of coping with the EMTP. Tom seems willing (within available resources) to repeat his valuable service of program setup, when we are ready this summer:

> "What are the differences ....? If they are significant, I would be more than willing to try to incorporate them -- and with a faster rerponse time."

As I have since told Tom, the changes are so massive that a whole new translation will be involved, as for all systems. Regarding response time, Tom need make no apologies. He did a good job on the "M21." version, despite other demands on his time, and lack of funding for technical support. It was a pleasure working with him.

x-1

0.51 CRAY-1 EMTP Setup (as used at Lawrence Livermore Lab.)

The CRAY-1 is a super computer, number one in the world for number crunching. No power company or conventional university is known to have one, though service can certainly be purchased commercially (time sharing).

Translation principles for the CRAY-1 were worked out in cooperation with Dr. Walter ("Waldo") G. Magnuson, Jr., of the Electronics Engineering Department. Only slight modifications to the CDC translator were required. One serious handicap as of the end of 1978 was the absence of overlaying by the system software (which had no virtual memory management). This has since been corrected, Waldo indicates. The translator which was used is "current" (since the "M22." discontinuity), so only minor updating will be required for "M27." use. In December of 1978 we generated a file of "M22.+" CRAY-1 EMTP FORTRAN, and sent it to Livermore for setup. At LLL, the EMTP is mostly used for fusion power supply design (by Mr. Alex Mihalka, principally), and operation of the CRAY-1 version was judged to be correct for this application. The solutions are apparently consistent with those generated by the CDC-7600 EMTP version, which is also operational at Livermore. Alex has reported a speedup by a factor of two and a half.

In a communication received on 14 May 1980, Waldo indicates that "LLL will be setting up the new version (summer of 1980) when it becomes available."

LAWRENCE LIVERMORE LABORATORY
Electronics Engineering Department
[illegible]
[illegible]
[illegible]

[illegible]
[illegible]

X-m

0.5m Burroughs EMTP Setup (as used at EBASCO)

Translation principle's for a Burroughs EMTP were worked out in cooperation with Mr. Stonewall ("Stoney") McMurray of Ebasco Services during much of 1978. It was this association which taught us that "M21." translation rules were not adequate to handle all major American computer systems, and we have been recovering ever since. For a detailed description of the structural reforms which grew out of the Burroughs consideration, see Ref. 8, Vol. VIII, 25 June 1978, pagination ANVB.

Well, an "M22.+" translation for Burroughs was eventually produced, and mailed to Stoney during December of 1978. But this has never been set up (one reason being that there were enough incompatibilities with the November 1977 EMTP User's Manual by that late date that utility to users would have been limited).

If Stoney is willing to set up a new translation during the summer of 1980, when we have a new, complete set of user instructions to match, this shall be done. There are two well-qualified users waiting outside the U.S.A., and a third having potential interest. So, one way or another, a new Burroughs translation shall be performed next summer, and shall be made available to the general public.

EBASCO

EBASCO SERVICES INCORPORATED
Two World Trade Center, New York, N.Y. 10048

UPDATE : On 22 April 1980 I talked to Stoney via telephone. He said that he has tentative approval from management to set up a new Burroughs EMTP version next summer. I said that I would pass the word on to Gerd Becker in Munich, and that I would be contacting Stoney in July or August. As with all translations, we will start with MICROMINIUTPF, to verify that everything is intact. Good, good, good!

BURROUGHS

BURROUGHS

BURROUGHS

X-n

0.5n SEL EMTP Setup (as used by LABOREL in Belgium)

Throughout the winter of 1979/1980, translation principles for a SEL EMTP version have been worked out with the cooperation of Mr. Germay of LABORELEC in Rhode-St.-Genese, Belgium. Mr. Steve Buroker of the Seattle (Washington) office of SEL (Systems Engineering Laboratories computer systems) has also been indispensable, as a local adviser.

On 2 April 1980 , an "M26." SEL EMTP translation was mailed to LABORELEC on tape for an attempted setup. Steve had earlier compiled key modules, so we believe that most details of the translation should be in order. But as of April 8, not even the receipt of the tape in Belgium can be reported.

I might mention that there are no known defects to the SEL version. That is, if setup is successful, it shall have full EMTP capability ---- all features will be operational, the code is variably-dimensioned, etc.

Based on our correspondence with Rhode-St.-Genese, LABORELEC is a most competent organization when it comes to computer details related to this program. But they are a long way away (the Air Mail service is poor, typically requiring 2 weeks or so). As with all other computer systems, we find it valuable to have a domestic contact. If anyone having interest in the SEL EMTP is to be found in North America, Program Maintenance at BPA would like to hear from him.

In a Telex (FAXGRAM) communication dated 14 May 1980, LABORELEC reported the following:

> "MAGTAPE RECEIVED 17 APRIL. RECEIVED MODULES SUCCESSFULLY COMPILED WITH MINOR ADAPTATIONS."

Because I apparently did not adequately explain the purpose and usage of the variable-dimensioning program "VARDIM", linkage editing with realistic dimensions had not yet been performed at that time. We remain in communication, however, so an executable image should not be too far off.

L/E

LABORELEC

LABORATOIRE BELGE DE L'INDUSTRIE ELECTRIQUE
BELGISCH LABORATORIUM VAN DE ELECTRICITEITSINDUSTRIE
SOCIETE COOPERATIVE COOPERATIEVE VENNOOTSCHAP

SECTION - 9 - SECTIE
SERVICE MATHEMATIQUE
WISKUNDIGE DIENST

ADRESSE POSTALE - POSTADRES
RHODE-ST-GENESE 1640 ST-GENESIUS RODE
TEL.: (2) 358.35.10
TELEX.: 22297 - LABORELEC - BRU. B.

X-0

C.50 MODCOMP EMTP Setup

MODCOMP is a trademark of the company Modular Computer Systems, Inc. of Fort Lauderdale, Florida. A number of models are manufactured, with the CLASSIC currently of interest for support of the EMTP.

Rules of MODCOMP FORTRAN have been studied, and the outline of principles for a translator have been established. There is an overseas party which will have a CLASSIC system installed toward the end of 1980 according to present plans, and it has been agreed that a translation shall be performed for them at that time.

As with all systems, it is desirable to have a domestic contact that has interest in the program. If there is any CLASSIC user in North America who would be interested in performing EMTP-related experiments (possibly going as far as the attempted setup of a current EMTP version), Program Maintenance at BPA would like to hear from him. There are known to be numerous MODCOMP computers in the American power industry, but most or all seem to be performing control (on-line monitoring and supervision) activities. We are actively seeking an installation that has enough memory to handle the EMTP. If no such cooperative party can be located, testing shall be performed overseas, some time around the end of 1980 or the beginning of 1981, it appears.

MODCOMP

MODCOMP

MODCOMP

MODCOMP

x-p

0.5p Japanese Computers of Various Types

"M21." versions of the EMTP have been tried on several computers of Japanese manufacturer, including FACOM , HITAC , and TOSBAC . Apparently these machines are structurally similar to American computers like IBM and Honeywell, so that adaptation of these latter versions is relatively simple.

Any interested EMTP user in Japan is referred for information to the established EMTP organization that has been formed by Aki:

Dr. Akihiro Ametani, Professor
Chairman of Japanese EMTP Committee
Department of Electrical Engineering & Electronics
Faculty of Engineering
Doshisha University
Kyoto 602
JAPAN

It is with no intent to downgrade individual Japanese computers that they have all been lumped into one section here. Rather, I just do not have enough specifics to describe each individually. All of the adaptation and usage of American EMTP versions has been done in Japan, on their own, without any help from Program Maintenance at BPA. I know nothing of the attributes of the machines, where they are located, what restrictions are applicable, etc. If the Japanese EMTP Committee would be willing to write up individual computer systems, one per page, I would happily insert that material in a later version of this Reference Manual. Current date is April 5, 1980.

57

X-8

0.5q Siemens EMTP Setup (as used at FGH in Mannheim, Germany)

FGH is our principal EMTP contact for Germany, and they happen to use a Siemens computer. Mr. Bernd Stein attended the EMTP short course in Madison last year (June, 1979), and when he returned to Mannheim, he proceeded to acquire the "M21." IBM package from a nearby user (Mr. Degens of Delft University in Holland). It seems that Siemens FORTRAN is of similar structure to IBM FORTRAN. Setup has been slow (Bernd is time sharing), but not due to serious compilation problems (though his existing standard compiler did fail to generate link-editable code for one of the error overlays, forcing Bernd to acquire a newer prototype compiler). As of March, 1980, testing appears imminent.

Anyone having interest in a Siemens version of the EMTP is referred to FGH. While no formal committment to set up a new translation during the summer of 1980 has been received, I would guess that this is likely ("he who uses other than the latest EMTP version is on his own;" and being on one's own in this business is both lonely and dangerous!).

If and when Bernd writes user instructions or other relevant information related to usage of his Siemens EMTP version, such material shall be placed in this section. The present material, written by Program Maintenance at BPA, is just filler, to reserve a place in the manual.

Finally, let me amplify on what is meant by FGH being our "principal EMTP contact for Germany." Bernd receives EMTP memos as they are written. When Reference Manuals are printed during the summer of 1980, a single shipment shall be made for Germany, to Mannheim. Other EMTP users or potential users in Germany are thus encouraged to contact Bernd, to receive information about EMTP usage and development. Just as there are now too many program users in Japan to be dealt with individually (fortunately we have Aki's Japanese EMTP Committee), so usage in Germany is expected to grow similarly. FGH has received the "franchise" to coordinate this usage for the mutual benefit of all.

FGH

FACHBEREICH 1
-Drehstromtechnik-
Mannheim-Rheinau, Hallenweg
Telefon (06 21) 89 50 51
Telex 462 279 fgh d
Drahtwort Megavolt Mannheim
Abteilung TR

Dipl.-Ing. B. Stein

**FORSCHUNGS-
GEMEINSCHAFT FÜR
HOCHSPANNUNGS- UND HOCHSTROMTECHNIK E.V.**

SIEMENS SIEMENS SIEMENS SIEMENS SIEMENS

0.6 User-Controlled Variable Dimensioning of the EMTP

The EMTP stores most problem data (all except that for synchronous machine models of Section 1.62) in tables which can be sized by the user at linkage-editing (loading; linking; mapping; etc.) time. The basic procedure was originally detailed in Ref. 8, Vol. II, 30 January 1975, pagination VARD and 17 April 1975, pagination RSFU. For the user's benefit, key points that are independent of computer system shall now be summarized. The user is also referred to the installation-dependent instructions for his computer system (Section 0.5a onward), since various aspects of the procedure depend upon both the brand of computer and the organizational usage. But universal aspects are:

Point 1 : With only a few relatively minor exceptions, the user can size all EMTP tables at will. There are currently 25 independent tables (or "lists") in the program, as per the following definitions:

List 1 : LBUS ---- The maximum number of problem nodes (busses).

List 2 : LBRNCH ---- The maximum number of problem branches. A 3-phase overhead line counts as three, etc.

List 3 : LDATA ---- The maximum number of R, L, C floating-point parameter values which are read from branch cards (such as for Pi-circuits and series R-L-C branches).

List 4 : LEXCT ---- The maximum number of problem sources. Each dynamic S.M. (see List 17) contributes 3.

List 5 : LYMAT ---- The maximum number of entries in the triangularized admittance matrix of the time-step loop. Storage is for the upper-triangle (including diagonal) only.

List 6 : LSWTCH ---- The maximum number of problem switches. Included are switch-resistance and switched-inductance elements of Sections 1.41 & 1.42. Diodes and values also count as switches.

List 7 : LSMAT ---- The maximum number of nonzero entries in the admittance submatrix [YBB YBC] of the time-step loop. This is the submatrix for the rows of partition "B" (switch nodes and pseudo-nonlinear element nodes), to be triangularized within the time-step loop whenever there is a switching operation.

List 8 : LPAST ---- The maximum number of modal past-history points, for distributed-parameter transmission lines.

List 9 : LNONL ---- The maximum number of nonlinear and pseudo-nonlinear elements in the problem.

List 10: LCHAR ----- Maximum number of points which define the characteristics of the nonlinear or pseudo-nonlinear elements of List 9 . Type-96 hysteretic inductors are an exception, however. For the first such element, 2*N + 8 cells are allocated, where N is the number of data cards that define the characteristic. Second and later elements might use the reference-branch feature, in which case requirements drop to six cells. See Section 1.31 for further details of this exceptional case.

List 11: NOUT ----- The maximum number of branch outputs, and also the maximum number of node-voltage outputs. Because multiplicity of this list is small, be generous and avoid later trouble.

List 12: LPEAK ---- The maximum number of output quantities.

List 13: LFDEP ---- The maximum number of frequency-dependent modes of distributed-parameter transmission lines which use the "WEIGHTING" modeling of Section 1.26b .

List 14: LWT ----- The maximum number of cells required to store frequency-dependent weighting functions A1 and A2 for the modes of List 13 .

List 15: LTAILS ---- The maximum number of cells needed to store the convolution line history for the exponential tails of frequency-dependent weighting functions of List 14 .

List 16: LJUMP ---- The maximum number of switches which utilize the "PART ENTER" feature. This is largely unused today (after Type-99 development).

List 17: LSYN ----- The maximum number of dynamic synchronous machines of Section 1.62 . A dual Type-59 machine counts as two. Current fixed sizes of the S.M. code (see final pages of Section 1.62) require that LSYN must agree; as sent out by BPA, this is LSYN = 4 .

List 18: MAXPE ---- The maximum number of branch or switch power and energy requests (column 80 punches having a value of "4").

List 19: LTACST ----- Maximum number of floating-point cells of total storage for all of the TACS tables. See Section 8. . A value of 137 is the minimum allowed (any small value will be so increased). A reasonable practical minimum for production problems might be 2000 . Serious TACS users will probably want more.

List 20: LFSEM ---- The maximum number of cells used to store recursive convolution parameters, for non-copied branch components of Section 1.27 .

List 21: LFD ------ The maximum number of cells used to store transformation matrices for the recursive convolution frequency-dependence modeling.

List 22: LHIST ----- The maximum number of cells which are used to store the convolution history associated recursive convolution (Section 1.27).

List 23: LSIZ23 ----- Used only for systems like Burroughs and PRIME where labeled COMMON blocks are not methodically placed in memory. Users of other systems can ignore this list, which provides dimensioning for the giant working vectors of node renumbering and the steady-state phasor solution. Conventional machines (IBM, Univac, VAX, etc.) have such dimensioning internally over-ridden by a fraction of the total /LABEL/ storage, so that the user-punched value is ignored by the variable-dimensioning program.

List 24: NCOMP ------ Maximum number of phases of compensation, at peak problem size. The actual maximum number of phases then varies inversely with the number of problem nodes. Use of NCOMP = 3 is most common, allowing for 3-phase compensation with full-size problems, 6-phase compensation with half-size problems, etc.

List 25: LSPCUM ----- Maximum number of floating-point cells of total storage for all universal machine (U.M.) tables. If U.M. modeling of Section 1.63 is not of interest, set to unity. Practical production usage allowing two 3-phase induction machines typically takes LSPCUM = 1500 .

An abbreviated version of this explanation appears as part of the case-summary statistics which complete the line-printer output of each data case being solved. See the example of Section 2.3 .

Point 2 : One step in the dimension-changing process is the execution of a separate variable-dimensioning program named "VARDIM" . This program reads 3 data cards in 10I8 format, obtaining therefrom the user-specified list sizes. The format for these 3 cards is as follows:

1	2	3	4	5	6	7	8	9	10
LBUS	LBRNCH	LDATA	LEXCT	LYMAT	LSWTCH	LSMAT	LPAST	LNONL	LCHAR
I8	I8	I8	I8	I8	I8	I8	I8	I8	I8

11	12	13	14	15	16	17	18	19	20
NOUT	LPEAK	LFDEP	LWT	LTAILS	LJUMP	LSYN	MAXPE	LTACST	LFSEM
I8	I8	I8	I8	I8	I8	I8	I8	I8	I8

21	22	23	24	25
LFD	LHIST	LSI323	NCOMP	LSPCUM
I8	I8	I8	I8	I8

Point 3 : As immediate verification of the list sizes applicable to any given EMTP simulation, the introductory heading which starts each new ca displays such figures. For example, (see next page)

```
ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP), DIGITAL (DEC) VAX-11/780 TRANSLATION AS USED BY BPA IN PORTLAND, OREGON 97208
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS.)= 04/19/80  13.30.25  ANY PLOTS BEAR SAME FIGURES.              VERSION = "M27."
IF IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE 564-PAGE EMTP USER'S MANUAL DATED NOVEMBER, 1977.
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF    /LABEL/   EQUALS 200123  INTEGER WORDS.      703  1050  2500    30  9500
   125  8100  3000    50   300   100   140     5  9000   400     9     4    30  6000   500    72   200  3000     5  3700
------------------------------------------------------------+---------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA | INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER
                                                   0         1         2         3         4         5         6         7
                                                   0         0         0         0         0         0         0         0
------------------------------------------------------------+---------------------------------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.               |BEGIN NEW DATA CASE
```

Also shown in this printout is a figure for the total number of words of labeled common (abbreviated as "/LABEL/") storage, which is the total storage requirement for all of the EMTP tables during the solution phases of the program. This figure will generally be needed by Program Maintenance should a computer system error occur during the execution (at which point the system rather than the EMTP will terminate execution), and the EMTP experts are forced to dig into the FORTRAN listing to find where execution stopped.

Point 4 : The "cost" of variable-dimensioning of the EMTP is a constant, pre-execution overhead which consists principally of the cost of loading (called linkage-editing, on IBM) the previously-compiled FORTRAN code. Once this operation has been performed, execution of the redimensioned EMTP will proceed at essentially the same speed as would a fixed-dimension program; there is negligible penalty during the actual solution phase of a typical EMTP data case.

Exceptions are the TACS code of Section 8. (which also uses offset-subscripting), and the universal machine (U.M.) code of Section 1.63 (which also assigns working locations for arrays as arguments of SUBROUTINE calls).

Point 5 : Certain primary-level non-solution overlays have giant working arrays (a maximum of one per overlay) which are sized the same as /LABEL/ except for a possible built-in offset which very crudely adjusts for the amount of code of the overlay. If the user wants to manually apply an additional offset to this storage, he can add a fourth data card as follows:

1. Punch an extra "9" in column one of the first data card that is read by VARDIM. This is taken as a special flag (VARDIM extracts it from LBUS before LBUS is used).

2. Add a fourth data card containing the extra desired offsets. The format is 10I8 , with one data field for each such primary-level non-solution overlay. Currently there are five: OVER29 , OVER31 , OVER43 , OVER44 , OVER45 .

Common usage of this feature is for virtual machines, where enormous list sizes are requested; unless specially compensated for, the giant working arrays would be dimensioned far beyond any reasonable program needs. In this case, offsets will all be negative. We do this on the VAX, where in March of 1980, offsets of -128500 are being used for the five overlays. For the record, the size of /LABEL/ is 207363 integer words, or in excess of 3/4 MB! Using the negative offsets saves on virtual address space for us, that's all.

Once the EMTP has been re-dimensioned, the resulting executable code can be saved for immediate re-use as often as the user wants, without any extra associated cost (other than for storage of the code, generally on disk). This is what makes the procedure so practical. Generally, a number of simulations of basically the same problem are made, so that the cost of the single dimension-changing operation associated therewith works out to be a very small fraction of the total simulation cost for the problem. One can afford to re-dimension for all large problems without appreciably increasing the cost of simulation. In fact, if one has realistic accounting charges which appropriately penalize usage of core storage during execution, one may indeed <u>save</u> money in this way (since running the jobs will require less core storage).

Should the variable-dimensioning program detect illegal or absurd data as having been supplied by the user in his attempt to redimension, it will terminate execution with an error message of which the following is an example:

```
************************************************************************************************************************
ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR E
ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR E
************************************************************************************************************************

   THE USER IS IN TROUBLE, UNLESS HE HAS MADE A DATA-PUNCHING ERROR.   VARIABLE-DIMENSIONING OF THE EMTP HAS
   BROKEN DOWN WITHIN THE SEPARATE VARIABLE-DIMENSIONING PROGRAM  'VARDIM' ,   IN PARTICULAR, ONE OR MORE OF THE
   USER-INPUTTED LIST SIZES MUST BE REJECTED AS BEING ILLEGALLY LARGE.   USER-SUPPLIED LIMITS (OR DEFAULT LIMITS,
   FOR ANY NON-POSITIVE DATA FIELDS) ARE AS FOLLOWS ....
      272   9876543        245         0         0        25        80         0         0         0
        0         0          0         0         0         0         0         0         0         0
        0         0          0         0         0
   SPECIFICALLY, THE USER-SUPPLIED VALUE WHICH WAS READ FOR LIST NUMBER    2  EXCEEDS  999999 ,
   WHICH IS UNREAL.    A VALUE OF    9876543    WAS READ FROM THE USER'S DATA CARD FOR THIS LIST.

************************************************************************************************************************
ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR E
ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR ERROR E
************************************************************************************************************************
```

Such an error message will come out on the line printer, just as the regular EMTP printout would have if the run had successfully continued. Hereafter, any output should be ignored. Ideally, the entire job should be instantly killed following such an error message, although this may not be possible or convenient on all systems. On some computer systems, an indirect method of killing the run, such as dividing by zero or accessing a memory location way outside the partition in which the job is being run, may be resorted to, in order to get the system to terminate execution of the job.

Normal execution of the variable-dimensioning program results in minimal printout which includes a pseudo-listing of the input data cards (3 or 4 in number). For example, as part of our BPA VAX EMTP setup (remember that this is a fully virtual machine, so list sizes can be enormous), the following was produced:

```
PSEUDO-LISTING OF DATA CARDS WHICH HAVE BEEN READ BY THE VARIABLE-DIMENSIONING PROGRAM  "VARDIM" .   ONLY
IF ALL DATA FIELDS ARE PUNCHED WITH  "CLEAN"  I8  INTEGER INFORMATION WILL THIS BE A TRUE LISTING.   DATA CARDS
ARE IN FACT READ IN AND THEN PRINTED OUT USING INTEGER VARIABLES AND  10I8  FORMAT.
-------------------------------------------------------------------------------------------------------------------
                                    0        1        2        3        4        5        6        7        8
                                    0        0        0        0        0        0        0        0        0
                                 ----------------------------------------------------------------------------------
1ST CARD (LISTS  1-10).         190000701    1030    2500       30     9500      125     6100     5000       30      300
2ND CARD (LISTS 11-20).         1       100     140        5     9000      430        8        4       30     6000      500
3RD CARD (LISTS 21-30).         1        72     200     3000        6     3700
SUPPLEMENTAL OFFSETS.           1 -187500 -182500 -187500 -182500 -187500
-------------------------------------------------------------------------------------------------------------------
NORMAL TERMINATION WITHIN  "VARDIM" .  THE
SIZE OF   /LABEL/   EQUALS  200123   INTEGER WORDS.
```

System-dependent control cards will be required to actually effect the dimensioning-changing process. Refer to your own computer system of interest in Section 0.5a onward. Should a cook-book procedure for doing the job not be found there, check with Program Maintenance of your company.

In order to parsimoniously re-dimension the EMTP, the user must know the multiplicity that is associated with each list which is to be re-sized. That is, he must know the number of arrays (vectors; columns of tables) to which each list applies. This handy information is automatically printed out by the EMTP following the error text which is associated with any overflow error stop of the program (KILL = 1). For example, in the case of network node (List 1) overflow, the tail end of the error-message printout appears as follows:

```
OF COURSE MAYBE THE USER WOULD LIKE SOME SUGGESTIONS AS TO WHY THE TABLE IN QUESTION (LIST NUMBER  9)
HAS OVERFLOWED.   IF SO, READ ON, GOOD BUDDY.   THE EMTP HAS A LONG-ESTABLISHED POLICY OF MERITORIOUS AND LAUDABLE
COOPERATION IN THE FORM OF CRYSTAL-CLEAR DIAGNOSTIC MESSAGES, SUCH AS THE FOLLOWING .....
    PAST-HISTORY POINTS FOR DISTRIBUTED-PARAMETER REPRESENTATION OF TRANSMISSION LINES ARE STORED IN MODAL FORM,
    ALWAYS.   EACH MODE REQUIRES STORAGE, WHERE THERE ARE AS MANY MODES AS THERE ARE COUPLED CONDUCTORS (E.G., A DOUBLE
    CIRCUIT LINE HAS 6 MODES.).   A CONSTANT-PARAMETER (FREQUENCY-INDEPENDENT) MODE CONTRIBUTES   TAU/DELTAT   ENTRIES,
    WHERE  "TAU"  IS THE MODAL TRAVEL-TIME OF THE LINE,  "DELTAT"  IS THE TIME-STEP SIZE, AND THE DIVISION INVOLVES
    INTEGER TRUNCATION FOLLOWED BY THE ADDITION OF UNITY.   FOR A FREQUENCY-DEPENDENT MODE, MORE PAST-HISTORY
    THAN THIS IS NEEDED, ENOUGH TO PERFORM THE  A2(T)  CONVOLUTION.   IN THE PRECEDING FORMULA, TAKE  "TAU"  TO BE THE
    TIME  "T2"  AT WHICH THE EXPONENTIAL TAIL ON  A2(T)  BEGINS (TYPICALLY 3 TRAVEL-TIMES OR SO).

IN ORDER TO EFFECTIVELY TRADE MEMORY SPACE AMONG THE DIFFERENT TABLES, ONE MUST KNOW HOW MANY ARRAYS THERE
ARE IN EACH TABLE (EFFECTIVELY).   THE FOLLOWING TABULATION SHOWS THE EFFECTIVE MULTIPLICITY ASSOCIATED WITH EACH
INDEPENDENT LIST ----- THOSE LISTS WHOSE LENGTHS ARE UNDER USER  CONTROL BY MEANS OF EMTP VARIABLE DIMENSIONING.
    -------------+---------------------------------------------------------------------------------------------
    LIST NUMBER  I   1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25
    -------------+---------------------------------------------------------------------------------------------
    FLOATING PT. I   6   5   3   6   1  12   2   2   8   3   1   4   8   1   2   0   3   1   1  26   2   1   #   *   1
    INTEGER      I   4   7   0   2   1  10   0   0  11   0   2   0   4   0   0   1  12   2   0   0   0   0   0   0   0
    TOTAL        I  10  12   3   8   2  22   2   2  19   3   3   4  12   1   2   1  15   3   1  26   2   1   #   *   1
    -------------+---------------------------------------------------------------------------------------------
  # --- USED ONLY FOR BURROUGHS AND PRIME AS OF MAY OF 1980.   OTHER COMPUTERS CAN IGNORE THIS LIST.
  * --- LIST 24 IS NOT COUNTED BY ITSELF.   INSTEAD, ADD THE VALUE TO THE FLOATING-POINT AND TOTAL COUNTS OF LISTS 1 AND 6.

                         CAUTION.   BE SKEPTICAL OF ABOVE  "PRESENT FIGURE"  ENTRIES, DUE TO ABNORMAL TERMINATION OF CASE.
------------------------------------------------------------------------------------------------------------------
ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR
ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR
------------------------------------------------------------------------------------------------------------------
CARD IGNORED IN SEARCH FOR NEW-CASE BEGINNING.     1  GENA  TRANS DECK
CARD IGNORED IN SEARCH FOR NEW-CASE BEGINNING.     1
CARD IGNORED IN SEARCH FOR NEW-CASE BEGINNING.     1  PRINTER PLOT
```

Note that the tabulation not only includes a total-multiplicity figure (bottom row of the table), but also decomposes this into integer and floating-point components. Such a distinction is important when working with a program version in which integer words are not as long as are floating-point words (e.g., the common double-precision IBM translation, wherein integer words are 32 bits (INTEGER*4), and floating-point words are 64 bits (REAL*8)).

Example: Suppose that a user wanted to increase list 11 and decrease list number 2 , all the while maintaining constant memory allocation.

a) On CDC where integers and floating-point words are of equal length (both 60 bits), the "TOTAL" row of the table shows that:

$$L_{11} * 4 \quad + \quad L_2 * 8 \quad = \quad 0$$

where L_k is the increase in size of list k .

b) For the most common case on IBM, with 4-byte integers and 8-byte reals,

$$L_{11} * (1 + 3/2) \quad + \quad L_2 * (3 + 5/2) \quad = \quad 0$$

Note that the multiplicity from the row marked "FLOATING PT." has here been used unchanged, while that from the row "INTEGER" has been divided by two in order to reflect their relative length of a half a floating-point word.

As to how large a computer memory partition is actually required for the execution of any particular program version —— or perhaps more appropriately, how much memory space is actually unused when a given standard memory partition of the computer is used —— the user should see a Program Maintenance expert. From the size of /LABEL/ as found in the heading printout which begins each new data case which is being solved (see Point 3), and a memory map for the standard EMTP version which has all default dimensions, the question is readily answered. The required partition size depends directly, and only, on the size of /LABEL/ , of course.

0.7 FORTRAN Data Format Specifications

Throughout this manual, data formats are indicated in FORTRAN notation, with symbols like F10.3, I8, A6, or E10.3 . A short, illustrative explanation is as follows. If unclear or incomplete, refer to a FORTRAN manual.

F10.3 ~ A decimal number is to be inserted in this space (field) of width 10 columns. In general, you should punch a decimal point; if you do not, it is assumed that digits in the last 3 of the 10 positions are to the right of the decimal point. As long as you punch the decimal point, the "3" is overridden, and positioning within the field is immaterial. Examples follow:

-39.5
132745 ~ gives 132.745
3.14159 ~ gives π

I8 ~ Integer data (no decimal point allowed) is to be inserted in the space (field) of width 8 columns. Integers should be punched "right-adjusted," as far to the right in the field as possible, since blanks are interpreted as zeros. Examples follow:

-39
1024
-99 ~ gives -99,000

A6 ~ An arbitrary collection of characters (letters; numbers; punctuation) is to be inserted in this field of width 6. Blanks are a special unique character, remember, so 'BUS A ' and ' BUS A' are not the same. Examples follow:

BUS-1A
1.3+A5
GROUND

E10.3 ~ A decimal number is to be inserted in the field of width 10 columns. Use of scientific notation, with a power of 10 following the symbol "E" , is added onto the previous rules for F-formats. Omitting the E and its following exponent is interpreted as a unity multiplier, so the E10.3 format then behaves just like F10.3 . Right adjust the number if an E is punched, since just as with the I-format, any trailing blanks are interpreted as zeroes. Examples follow:

1.609E3 ~ gives 1609
1.609E3 ~ gives $1.609 \cdot (10)^{300}$
3.1415926 ~ gives π
-5.1 ~ gives -5.1
-5.2E-4 ~ gives -.00052
5.2E+4 ~ gives 52000

There also is the option of free-format data specification, for half or more of the different EMTP data structures. The idea is simple. Rather than positioning data fields in fixed column locations, there is an ordering from left to right, with a separator character (usually a comma) used to delineate the field boundaries. If more than one data card is needed for the string of data items, a continuation character (usually a dollar sign) is used rather than a separator character, which means that another data card is to be read before extracting the next data item.

To illustrate, consider the special request word "POWER FREQUENCY" which provides for redefinition of the steady-state frequency (see Section 1.0c). Using free-format, this reads:

```
          POWER FREQUENCY, 50
```

Rather than punching 50.0 in columns 33-40, then, ", 50" has been appended to the key word. The comma is a separator character, dividing the key word from the parameter; the space after it is optional, since blank characters are ignored in this mode. Note also that no decimal point has been punched, for integers and floating point variables are interchangable when using free-format. For a realistic, full-scale application of free-format usage, see the data cards punched by the transformer impedance matrix program of Section 7.1 .

In case the user wants to redefine the free-format characters CSEPAR (for field separation) and CHCONT (for continuation), see Section 1.0g6 . This is not recommended, however.

More serious is the question of which EMTP data structures can be handled by the EMTP free-format. There is no simple rule. Read Section 1.0g6 for further perspective. In any case, be skeptical, and always test the capability before relying on it for the coding of any substantial volume of data.

For numeric data fields, blanks are ignored, no matter where they appear. For example, ", 10 3," is the same as ",103," .

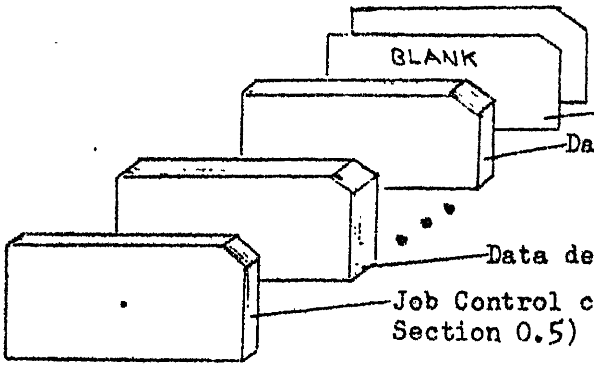
For floating-point numbers, either "D" or "E" can be used to indicate a power of ten. Thus "1.E+9" and "1.D+9" are identical. Also, the plus sign preceding an exponent can be dropped, so that "1.E9" is equally valid.

Errors with the use of EMTP free-format capability can be confusing sometimes, due to the fact that execution will not always be stopped immediately. A KILL = 166 error flag can be set within module "FREFLD" , and there should be a line or two of immediate printout announcing the fact. But there is no easy way to immediately transfer control to the EMTP error overlays. It may take some time before an IF (KILL .GT. 0) error check will be encountered, at which point the formal EMTP error stop ("You lose, fella") will result.

Users should also be warned about possible precision problems with the use of EMTP free-format, as documented in Ref. 8, Vol. X, 3 July 1980, page MSDO-10. At issue is the accuracy of the library function handling of FORTRAN exponentiation ("**" operation). A standard procedure for avoiding the issue is to rely on the system-dependent READ (KK, *) operation. If full precision of the result is a concern of the reader, he should check with Program Maintenance about module "FREFLD" for his computer system. He might also look at the installation-dependent instructions (Section 0.5 onward).

1. STRUCTURE OF EMTP INPUT DATA

Any number of cases can be run with one job submittal. Simply stack the data decks for the different cases:



Special end-of-job termination card if required by user's system.

Blank card for termination of case

Data deck for n-th case

Data deck for first case

Job Control cards (see Section 0.5)

a) DATA DECK : Each EMTP problem must be fully described in a data deck (or data case) which is composed of the following parts, in the order listed:

1) Cards to begin a new data case. Included are a "BEGIN NEW DATA CASE" card, special request cards of various types (if any), and finally the EMTP miscellaneous data cards.
2) Specially-requested extensions to miscellaneous data cards.
3) Cards which define any TACS (control system; digitally-simulated analog computer) representation.
4) Cards for linear and nonlinear branches, transformers, and transmission lines (or cables), terminated by a blank card.
5) Cards for electric-network switches, diodes, ac/dc converter valves, switched-resistance elements, and switched-inductance elements, terminated by a blank card.
6) Source cards for electric network (voltage sources, current sources, dynamic synchronous machines). These are terminated by a blank card.
7) Cards for over-riding the internally-calculated initial conditions (which come from the phasor steady-state network solution).
8) Node-voltage output specification cards. These are terminated by a blank card if the specification is selective. But if all node voltages are requested by means of a "1"-punch in column number 2, then there is to be no blank terminator card.
9) Cards for specifying Type 1-10 EMTP source functions point by point. There is one card for each time-step, terminated by a "9999" card.
10) Batch-mode plotting cards (either for CalComp plotting or line printer plotting), terminated by a blank card.

This data structure is for a single deterministic transient simulation, which is the most common case (see next paragraph for exceptions). Often data classes 2) , 3) , 7) , and/or 9) are not required, and can simply be omitted. If data class 5) , 5) , or 10) might possibly not be needed due to the nature of the problem under consideration, then only the terminating blank card alone is required (and must never be forgotten).

There are valid EMTP data cases which do not have the above structure. The first class of such exceptions involves usage of the EMTP supporting routines. Examples are "LINE CONSTANTS" (used to calculate the constants of overhead transmission lines) and "REPLOT" (used for the batch-mode plotting of a previously-solved data case). The second class of such exceptions involves the usage of multiple-simulation features such as for statistical overvoltage studies (the "STATISTICS" feature of switch cards). Details of such exceptions are covered in the body of this User's Manual.

As seen from the preceding explanation of data-deck structure, the blank card is extensively used as a terminator card, for various classes of data. Sometimes a user is confused as to the purpose of one or more blank cards, and would like to add some explanation of the meaning. This is easy; just use "BLANK " for the first six characters, and the remainder of the card is available for comment. For example, "BLANK CARD ENDING BRANCH CARDS" . The EMTP recognizes all such cards, and blanks them out internally, before processing them (but after listing on the printer; they appear as punched by the user) .

Just as with FORTRAN programming, "comment cards" of English-language (or French-language, etc.) text may be added to the data deck at any point. The punching of "C " in columns 1-2 is all that it takes for the EMTP to ignore a data card as it is inputted. Do not forget the blank in column two, however (this is a rule change since the last manual of November, 1977, since "M21." versions). Such comment cards will appear as part of the input data listing, but will be otherwise disregarded by the EMTP.

Also, whole blocks of data can be so ignored by the EMTP if recourse is made to $DISABLE and $ENABLE cards. Refer to Section 1.-D , as well as the installation-dependent information for your computer system in Section 0.5a onward.

Just as with FORTRAN programming, "comment cards" of English explanation may be added to the data deck at any point. The punching of a "C" in column one is all that it takes. Such records will appear as part of the input data listing, but will be otherwise disregarded by the EMTP.

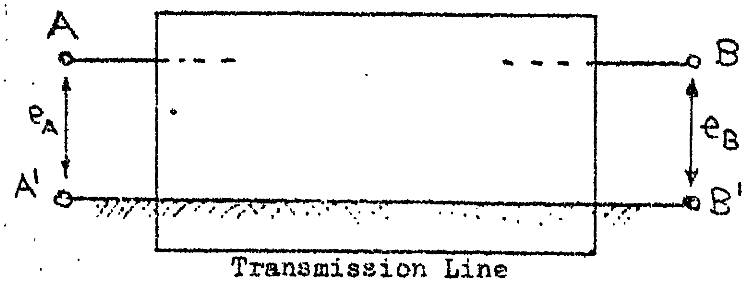
b) DESCRIPTION OF THE ELECTRIC NETWORK :

Each non-ground node of the electric network is given a 6-character alphanumeric name. Only identical sequences of 6 characters will be recognized as one and the same node. Therefore 'VOLTS ' will be a different node than ' VOLTS'. '   ' (6 blanks) is the name reserved for ground (common reference or local ground). Special names which the user should avoid are "......" , "TYP-16" , "HEIGHT" , "MARGIN" , "SMOOTH" , "TARGET" , "BRANCH" .

Branches are identified by their data and the names of the nodes to which they are connected.

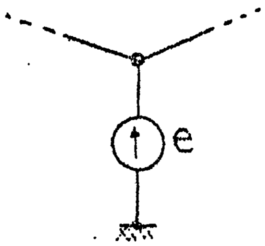
Switches are identified in same way as branches.

Voltage and current sources are identified by node names and are assumed to be between the node and the local ground. If no ground resistance is involved, then "ground" is the common neutral. Otherwise "ground" means local ground.

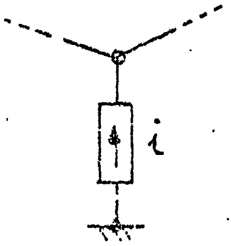


Transmission Line
with Ground Resistance

e_A is voltage between terminals A and A';
e_B is voltage between terminals B and B'.



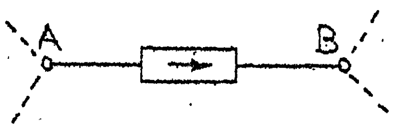
Voltage Source



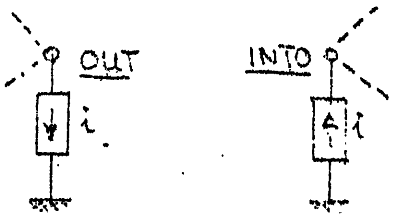
Current Source

Node voltage is the voltage from node to local ground.
Branch voltage is the voltage difference across a branch.
Output voltages of the EMTP consist of an arbitrary selection by the user of these two types of voltages. If one wants a voltage difference where no branch exists (or where such output is otherwise not permitted), the user need only add a very high resistance branch between the nodes in question, and request thereupon the branch-voltage output. Acceptable values for this purpose are 1.E18 for Univac and Honeywell/GE, 1.E35 for IBM, and 1.E100 for CDC.

Current source between 2 nodes: A current source from node A to node B can be represented by two current sources, one out of node A and one into node B.

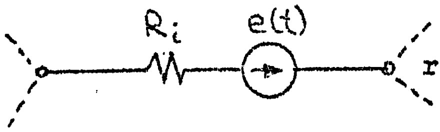


represent as:

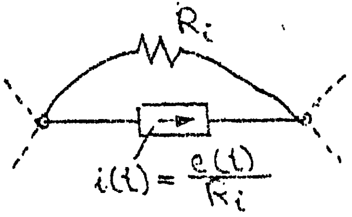


This representation does not change any impedances between nodes A and B.

Voltage source between 2 nodes: If the voltage source between 2 nodes has an internal resistance, then make an equivalent current source out of it and treat it as such (see Point 9), Section 1.5). For example,

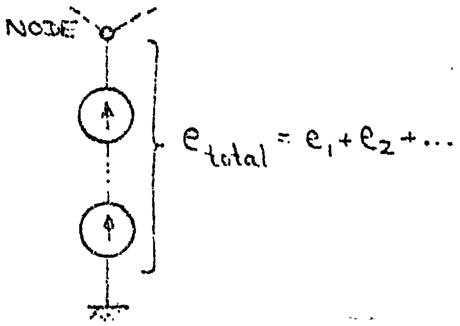


represent as:

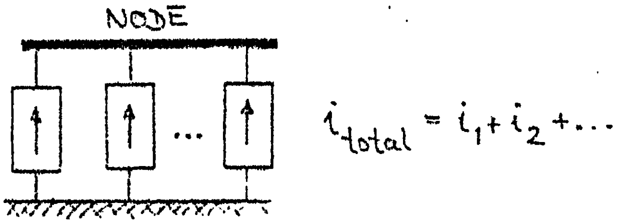


If $R_i = 0$, then the voltage source between 2 nodes cannot be handled by this program.

Voltage sources in series: If more than one voltage source is specified at the same node, the voltages will be taken in series from ground to that node. This permits the representation of a complicated wave form as a sum of different functions.



Current sources in parallel: If more than one current source is specified at the same node, the currents will be taken in parallel from ground to node.



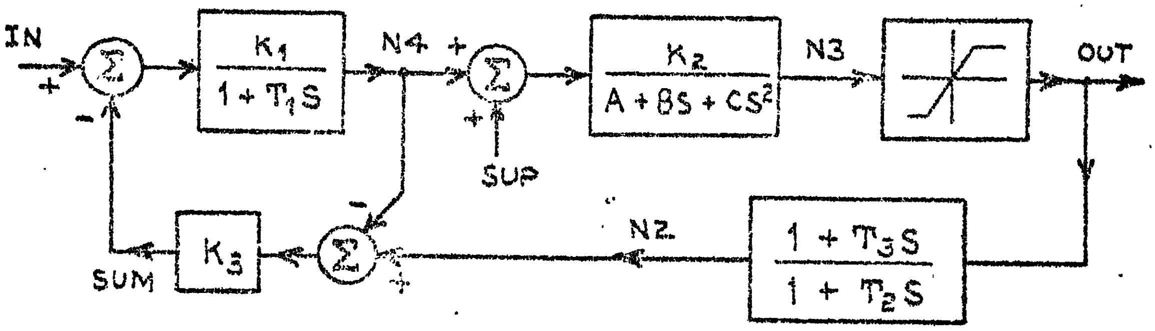
Simultaneous voltage and current source on same node: If voltage and current sources are specified at the same node, the voltage sources override and the current sources are ignored. Both forms cannot exist simultaneously.

Connectivity Requirement: With all nonlinear and time-varying branches deleted, the resulting equivalent resistive network which is solved at each time step must be connected. See details in Section 1.3-D.

C) DESCRIPTION OF CONTROL SYSTEMS

The preceding summary has considered only the description of the electric network (resistors, capacitors, voltage sources, etc.). The modeling of control system dynamics is separate and distinct, as provided by the TACS code of Section 8.

Control system blocks can take various forms : Laplace transfer functions, summing junctions, nonlinear algebraic operations (multiply, divide, square root, etc.), logical operations, etc. The output of each control system block is given a distinct 6-character alphanumeric name, so as to identify the signal in question. Such blocks can be defined and interconnected arbitrarily by the user, forming a control system circuit. One such sample illustrative diagram is shown below:



It might be mentioned that any given 6-character alphanumeric name can be used once in TACS and also once in the electric network; there is no confusion by the EMTP, since the TACS solution is completely separate from the electric network solution. Such double usage is in fact recommended in the case of interface quantities, to remind the user of the connection.

Note the one-way flow of signals (unlike for the electric network, control system components have an orientation, and are not bilateral). Signal sources which serve as input to such control circuitry can be either self-contained (e.g., a sinusoidal oscillator, or a step function), or can be controlled by the electric network (e.g., any node voltage or any switch current can be used as a TACS source). Likewise, any TACS variable can be passed back to the electric network for control purposes (e.g., the status of an electric network switch can be controlled by TACS, as can a voltage source, or the field voltage of a dynamic synchronous machine. Variables of this type which are passed back and forth between the electric network and TACS are referred to as interface quantities.

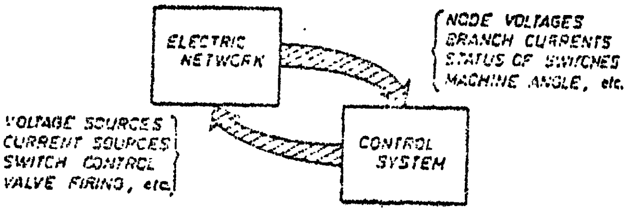


Fig. 7. Dynamic interaction between electric network and control system.

D) $-CARDS for Special File Operations

The dollar sign "$" is conventionally used as the continuation character CHCONT for free-format specification (see Section 1.0g6). But when placed in column number one, and when followed by the appropriate key word, it represents a request for a higher-level file operation.

The exact form of $-cards, as well as the list of available key words and their meanings, will vary somewhat from one computer system or installation to another. If no instructions are to be found in Section 0.5a onward for the computer system of interest, check with the on-site Program Maintenance. Should they in turn deny all knowledge, procure a listing of the FORTRAN code of module CIMAGE (see near the beginning of Section 0.5 for the location), and study it. If $-cards are allowed, there should be very conspicuous comment cards and DATA statements which define the acceptable key words. For the original VAX implementation, see Ref. 8, Vol. X, 20 January 1980, pages ANFC-1 through 7.

One trivial $-card function whose form is invariant on all systems (and which can clearly be implemented on any system) is the $DISABLE/ENABLE feature. A $DISABLE card tells the EMTP to treat all following data cards as if they were comment cards, until the subsequent appearance of a $ENABLE card. This is a very handy feature for big blocks of comments, or for the temporary removing of components from a data case without actually throwing the records away (one might want to later restore them).

Another universal $-card is the $LISTOFF/LISTON feature. A $LISTOFF card tells the EMTP not to print and interpret data cards which follow. This continues until a $LISTON card is encountered. The object is to minimize the size of the output file by omitting the listing and interpretation of blocks of data which have been tested and used before. This is particularly advantageous for users of slow (e.g., 300 baud) typewriter terminals, to speed the printout.

A third universal $-card is the $DIAGNOSTIC,M card, where "M" is an integer (diagnostic printout control variable IPRSUP ; see Section 1.0h, integer miscellaneous data card). Within the overlay currently being executed, this allows redefinition of the dumping level. When the current overlay is left, however, the $-card definition is lost. Free-format is used for the ",M" part, so imbedded blanks are permitted here. Printout can be turned off later in the overlay using $DIAGNOSTIC,0 (remember that level zero implies none). Use of this $-card does not replace the "DIAGNOSTIC" special-request card of Section 1.0g7 (for diagnostic control overlay by overlay). In fact, this is why the $-card definition is local to the overlay: because IPRSOV is used to reset IPRSUP every time a new overlay is begun.

A fourth universal $-card is $STOP, to stop EMTP execution

Finally, the universal $VINTAGE,M card allows the user to choose between old and new data formats on a component by component basis. Here integer constant "M" characterizes the age of the data (only 0 and 1 have meaning as of the inauguration in June of 1980, for "M28." versions). Data options will be described later in the manual, along with the components which allow such choice.

By far the most important $-card is $INCLUDE , which was named after a comparable FORTRAN feature (in the Univac and VAX dialects, anyway). Also on this data card will be the specification of a file, which will vary from system to system. When $INCLUDE is encountered, the EMTP switches to the named file for all input. This continues until an end-of-file is encountered, at which time reading from the original input file (connected to unit LUNIT5) is resumed.

The user of any non-universal $-card feature must remember that his data case is installation-dependent. He must not try to solve such a data case on a different computer system than it was set up for, without consideration of needed changes to one or more $-cards.

1.0 CARDS TO BEGIN A NEW DATA CASE (INCLUDING MISC. DATA CARDS)

Each new data case which is to be solved must be begun with one or more of the data types described in the following subsections. Structurally, there are an indeterminate number (possibly zero) of special-request inputs which come first, in any order. The miscellaneous data cards of Section 1.0h only come after the last of any such special-request inputs for the data case.

It should be mentioned that free format is particularly useful for special-request inputs, for the user who is assembling data via a conventional computer terminal (on which column position is not intuitively obvious). Take the "FREQUENCY SCAN" output of Section 1.0f as an example. Using free format, a valid sample card image is as follows: "FREQUENCY SCAN, 10., 6.0, 100., 0" . Even further abbreviation is possible for the really-lazy data assembler; rather than using the full request word, an acronym made up of the first letter of each sub-word can be used. In this case, "FREQUENCY SCAN" can be abbreviated to "FS" , if desired.

In the order that they are explained in subsequent sections, the following key words are recognized at this point of EMTP data input:

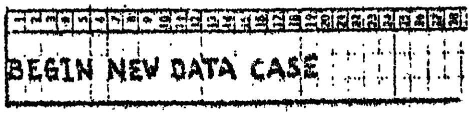
BEGIN NEW DATA CASE
PRINTER LINES PER INCH
PLOTTER PAPER HEIGHT
LIMIT ON PLOT OSCILLATIONS
REDEFINE TOLERANCE EPSILN
HIGH RESISTANCE
POWER FREQUENCY
REPLOT
FILE REQUEST
USER IDENTIFICATION
ABORT DATA CASE
KILL CODES
AVERAGE OUTPUT
ABSOLUTE TACS DIMENSIONS
RELATIVE TACS DIMENSIONS
TABULATE ENERGIZATION RESULTS
STATISTICS OUTPUT SALVAGE
OMIT BASE CASE
MISCELLANEOUS DATA CARDS
CHANGE PRINTOUT FREQUENCY
BEGIN PEAK VALUE SEARCH
TIME OF DICE ROLL
PEAK VOLTAGE MONITOR
ABSOLUTE U.M. DIMENSIONS
RELATIVE U.M. DIMENSIONS
START AGAIN
TIME STEP LOOP
POSTPROCESS PLOT FILE
NODE VOLTAGE OUTPUT
XFORMER
SATURATION
WEIGHTING
LINE CONSTANTS
SEMLYEN SETUP
AMETANI SETUP
CABLE CONSTANTS
HAUEF SETUP
ANALYTIC SOURCES USAGE.

TACS EMTP SOURCES
FREQUENCY SCAN
RENUMBER BYPASS
MODIFY DELTAT

FREE FORMAT
DIAGNOSTIC
INPUT LIST OFF

1.0a Optional Case-Separation cards

While not mandatory, it is good practice for the EMTP user to make the very first card of each data case a special case-separation marker:



See the sample data listing of Section 2.3 for an example of this usage.

For runs which terminate normally, or single-data-case runs, this card just described serves no operational purpose; it does of course appear on the 80-column input data listing, with appropriate interpretation on the left, but that's all.

On the other hand, should the EMTP decide to prematurely terminate execution of a particular data-case solution (with an EMTP error message), then a case-separation marker does come in handy. The EMTP automatically steps over remaining input cards, discarding them one at a time until it finds such a "BEGIN NEW DATA CASE" record. At this point, a new data case is known to begin, so the EMTP can correctly recover to solve the just-found following case. This is referred to as EMTP error-recovery capability, during multiple-data-case runs.

Yet suppose that it was during solution of the final data case of the run that a fatal EMTP error termination occurs. In this case there would be no following data case, so further solutions would not be possible. To distinguish this situation , the final data case should always be followed by a "BEGIN NEW DATA CASE" card and a blank card ---- which will then end execution. The blank card is in this situation read as the start of a new data case, and lack of any punching on it is recognized by the EMTP as the end of all data cases.

It should be emphasized that "BEGIN NEW DATA CASE" cards must be properly positioned in the data deck; they do not in any way alter the need for blank termination cards (the function of which is explained elsewhere in this manual). The identity and function of these special cards is recognized by the EMTP in only two places:

1. Following an EMTP fatal error, such cards are watched out for, as other records of the input data are discarded.
2. Following normal completion of the solution for any particular data case, the very first non-comment record of the following data case will be checked for "BEGIN NEW DATA CASE" .

Any other placement of these key cards will generally lead to program bomboff, since the alphanumeric text will be either read or decoded numerically, which is impossible, and will lead to a system error.

1.0b Blank Card for the Termination of EMTP Execution

The normal termination procedure for the EMTP is to have the first card of the following (non-existent) data case completely blank; by agreement, this means that there remain no more data cases to be solved, and EMTP execution is terminated.

In order to protect against bomboff by the operating system in the event that data should run out on the input file of the EMTP, the just-mentioned final blank card should always be preceded by a "BEGIN NEW DATA CASE" card. This is as per Section 1.0a .

1.0c Special Request Cards to Redefine Built-In Program Parameters

There currently are three plotting parameters which are given default or nominal values by the EMTP, but which can be redefined at the start of any new data case, if this is desired by the user. These are as follows:

Variable "LNPIN" :

PRINTER LINES PER INCH		LNPIN
5A4		I8

Used only in conjunction with the line-printer plotting of graphs, variable "LNPIN" gives the number of lines per inch to which the line printer has been set. Since both 6 and 8 lines/inch are common in the USA, the user should check with Program Maintenance as to which default value his particular program translation has been set for. In any case, redefinition is by means of the above-listed special request card which carries the text "PRINTER LINES PER INCH" in columns 1-22, and the new desired value for "LNPIN" punched in columns 33-40 as I8 information.

Variable "SZPLT" :

PLOTTER PAPER HEIGHT		SZPLT
5A4		E8.0

Variable "SZPLT" is the height of the graph paper upon which Calcomp plots are to be drawn. Protection against pen movements which would go off the top of the paper (higher than "SZPLT" inches, relative to the location where the pen is initialized at the bottom of the paper) is provided by this variable. The nominal value presently used for "SZPLT" is 10.0 inches, though this may vary from translation to translation; the user should consult with Program Maintenance to find out what built-in value exists for his program. In any case, redefinition is by means of the above-listed special request card which carries the text "PLOTTER PAPER HEIGHT" in columns 1-20, and the new desired value for "SZPLT" punched in columns 33-40 as E8.0 information.

Variable "NSMTH" :

LIMIT ON PLOT OSCILLATIONS	NSMTH
	I8

Variable "NSMTH" is a limit on the number of successive ups and downs which a curve being plotted is to be allowed, before the averaging of successive ordinates for all later time is to be instituted. A default value of 50 is normally used (assigned in installation-dependent module "SYSDEP" ; see Section 0.5 for location). In any case, redefinition of this variable is possible by means of the special request card reading "LIMIT ON PLOT OSCILLATIONS" ; the new oscillation limit is to be punched in cols. 33-40.

Currently there also are three non-plotting parameters which can be redefined by the user, if need be, as follows:

Variable "EPSILN" :

REDEFINE TOLERANCE EPSILN	E8.0
	EPSILN

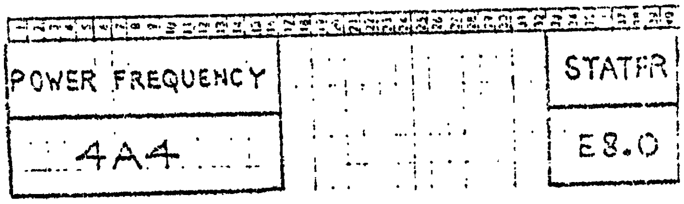
The familiar floating-point miscellaneous data parameter "EPSILN" (see Section 1.0h) is used far more than for the stated reason of checking matrix singularity. Often the EMTP wants to know whether a floating-point result is getting small, and "EPSILN" (possibly scaled by a power of ten) is usually used as the standard of comparison. This may occur in the solution of EMTP data cases which have no miscellaneous data cards, however, so that the user would otherwise have no control over this important parameter. A "LINE CONSTANTS" or "CABLE CONSTANTS" data case is such an example. By means of the "REDEFINE TOLERANCE EPSILN" request card shown above, the user can redefine this value at will. The default value is set in installation-dependent module "SYSDEP" (see Section 0.5), and typically has a value of 1.E-8 for REAL*8 translations, and 1.E-5 for 36-bit translations.

Variable "KPARTB" :

HIGH RESISTANCE	I8
	KPARTB

The Type-50 to 53 SCE S.M. source component of Section 1.62 is compensation based. To ensure connectivity among the armature phases in cases where there is no regularly-connected 3-phase or 6-phase line, high-impedance resistors are internally added by the EMTP. Type-99 pseudo-nonlinear elements (see Section 1.28) also have large resistance internally added, always. The value of resistance in both of these cases is normally based on the near-zero round-off tolerance "FLZERO" which is defined within installation-dependent module "SYSDEP (see Section 0.5). For example, most REAL*8 translations (IBM, VAX, PRIME, SEL, etc.) will have FLZERO = 1.E-12 . The EMTP uses resistance value RINF = .01/FLZERO ohms, or 1.E+10 for REAL*8 machines. Generally no problem in this case. But for lower-precision translations like the 36-bit Honeywell and Univac ones, the resulting RINF value will drop, and may be bothersome. By means of the "HIGH RESISTANCE" request card shown above, the default value of RINF can be replaced by 10**KPARTB . The user thus has control within a power of ten.

Variable "STATFR" :



Variable "STATFR" is the synchronous power system frequency, in Hertz. This will normally be 50 Hz or 60 Hz , depending on the translation being used (the definition is made within installation-dependent module "SYSDEP" of overlay number 1). Yet special cases can be of interest (e.g., the 400 Hz usage of the aircraft industry, or the usage of both 50 Hz and 60 Hz within Japan). In any case, if the user wants to change variable "STATFR" , he need only punch a card according to the above format; the text "POWER FREQUENCY" is to be punched in columns 1-15 , and the desired new power frequency goes in columns 33-40 as E8.0 information.

If the user chooses to alter two or more such parameters, the order of the requests is immaterial. If the data case in question is a "REPLOT" case, the above-described parameter redefinition cards (if any) must precede the "REPLOT" card (see Section 1.0d), since immediately thereafter program control will be transferred to plotting.

1.0d "REPLOT" ---- Calcomp Plotting of Previously-solved Cases

If a previously-solved data case had miscellaneous data parameter 'ICAT' set to 1 or 2 , then the plot data points of that solution were saved on disk as a permanent file. Should the user now, at a later time, wish to do Calcomp batch-mode plotting from this data, he need only precede his plot cards by the following "REPLOT" request card:

REPLOT	MM/DD/YY HH.MM.SS		IPRSUP
A10	20A1		I8

Cols. 1-6 : Must contain the key request word "REPLOT" .

Cols. 11-30: The date and time which are uniquely associated with the solution to be plotted are to be punched between columns 11 and 30. This date and time will be found in the line-printer heading which began the output of the solution to the data case which is now to be plotted. Only the six decimal digits of the date and the six decimal digits of the time are required or actually used, with blanks or separation characters like "/" and "." totally ignored by the EMTP. Hence within the column 11 to 30 boundary, it is free-field format.

Cols. 73-80: Parameter controlling diagnostic printout; leave "IPRSUP" blank (or punch a zero) for production runs. See further definition associated with usage on integer miscellaneous data card.

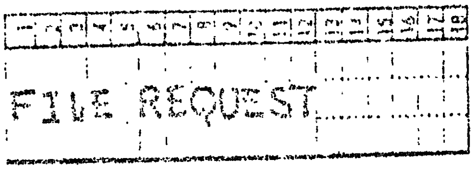
Warning! Before blindly trying the just-described feature for the first time, a user is advised to first read the installation-dependent instructions for his own computer system (in Section 0.5a onward). If "REPLOT" is not explicitely mentioned therein, check with more experienced users, or with Program Maintenance of your organization. The "REPLOT" feature is quite installation-dependent, and may not even be activated on most systems. With the advent of interactive CRT plotting (see Section 5.), it is falling into disfavor. On some systems (e.g., VAX as used at BPA in 1980), there may be restrictions as to the form of the file name (date and time), or the use of free-format only (rather than the fixed-format which is shown here). The fixed-format just described was used with BPA CDC during and before 1978; it is retained here only as an illustration of one possible high-level implementation.

A data case in which the user wants to produce Calcomp plots by means of the "REPLOT" feature then consists of the following components:

1. First, a "BEGIN NEW DATA CASE" card, if so desired. This is optional, as per Section 1.0a description.
2. Possible special request cards to redefine built-in EMTP plot parameters, as per Section 1.0c . These have key request-words "PLOTTER PAPER HEIGHT" & "PRINTER LINES PER INCH" .
3. Then the "REPLOT" card as just described.
4. Finally, the plotting cards, as described in Section 1.10 .

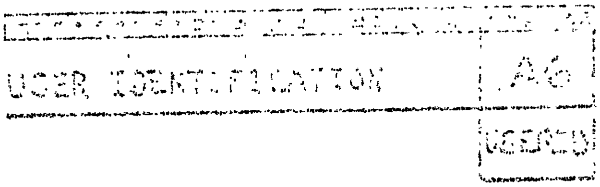
1.0e Calling of Installation-Dependent Module "MIDOV1"

The principal installation-dependent module that is called at the start of execution of each data case is "SYSDEP". But there is yet another such module in overlay 1 which is used for initialization (see Section 0.5): "MIDOV1". For some computer systems, for certain special types of data cases, it may be necessary or desirable to have "MIDOV1" called at a certain point during the data input. This is possible, by means of the special request card "FILE REQUEST" (see format at the right). But a warning should be issued: do not use this without the knowledge and approval of Program Maintenance.



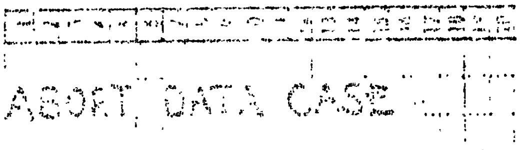
1.0e1 Redefinition of 6-character Text "USERID"

In conjunction with the batch-mode plotted output (CalComp) output of Section 1.10, there is the problem of identifying which plot belongs to which user. Of course, individual installations may have special exotic ways, in which case there is no problem. But if this is a problem, the EMTP comes to the rescue with six characters of user-name type identification "USERID". For sophisticated implementations, the assignment of an identifying name will automatically be performed within installation-dependent module "SYSDEP" (see Section 0.5), so the user need not be concerned by it. During and before 1978, this was done at BPA for the CDC installation. But for some systems it may be difficult to obtain such user identification at the FORTRAN level, or the user may want to over-ride it in any case. Such a redefinition of the six-character contents of "USERID" is possible, using the following special-request card:



1.0e2 Card to Disable an Entire EMTP Data Case

Suppose a user has an EMTP data case which he wants to keep, but which he also knows is defective for one reason or another. To prevent the running of such a data case (and subsequent bombout of the entire job of several data cases, for example), a user can resort to the key-word card shown immediately below. Once this is encountered, the EMTP will skip input records until the next "BEGIN NEW DATA CASE", at which point execution begins anew.



1.0e3 Request for the Printing of EMTP KILL Codes (Error Messages)

It is sometimes handy to be able to generate the text of any particular fatal EMTP error message (KILL code) without actually having to set up a data case which will so bomb off the machine during execution. This is possible for most systems, using the request:

KILL CODES	I8	I8
	KILL1	KILL2

The key-word "KILL CODES" begins in column 1, and KILL1 and KILL2 are the beginning and ending KILL numbers of the consecutive KILL codes which are to be printed. Of necessity, KILL2 must not be less than KILL1 .

A few words about the functioning of this feature are in order. As of April of 1980, EMTP error messages are contained in five overlays: 51, 52, 53, 54, and 55. The first four of these have 50 error messages each, and the last is well short of this limit (when we reach 50, a new overlay is created). As we loop over KILL codes, control always begins in overlay 51; then a transfer is made to the overlay that has the error message in question (e.g., overlay 52 for KILL between 51 and 100); then a transfer is made to overlay [illegible], to the end of the loop; finally, if this is not the last error message, control passes back to overlay 51 where it began, and the cycle repeats. Of these three overlay transfers, not that one can be omitted (only two are actually required if the error message is found in overlay 51 or overlay 55). Now, for computers with [illegible] (non-virtual), all of this rolling of code in and out can be time consuming. In the Vol. VIII EMTP memo of Nov. [illegible], page [illegible] [illegible] CDC-6500 times as part of my bigger argument for virtual architecture. The figure presented is about 10 seconds of I/O time for each error message, worth perhaps [illegible] cents. On such a computer, then, do not expect to dump 100 or 150 error messages rapidly and economically.

Another caution is in order. Systems which do not allow the printing of garbage may have trouble with this feature. VAX is one such system, and the printing of a range of KILL codes will typically end prematurely with an I/O complaint by the operating system. We never had that problem with CDC. If this becomes a problem, perhaps later we shall carefully initialize all variables of /BLANK/ before the printing begins; but as of April, 1980, there is no such initialization, so a lot of garbage is printed.

1.0e4 Request to Average EMTP Output

AVERAGE OUTPUT

By means of the special-request text "AVERAGE OUTPUT" beginning in column one, the user signals his intention that successive values of EMTP output variables be averaged before printing and plotting. The mathematics of EMTP solution are not affected; this is just a massaging of the answers at the time answers are printed and written to the LUNIT4 plot file. By averaging is meant the arithmetic mean of the current and the preceding variable value, (Vnew + Vold)/2 .

For studies where EMTP output variables are smooth functions of time, the "AVERAGE OUTPUT" request would have negligible effect, and should not be used (it just adds a small error to the answer). But there are problem cases like that of the hanging inductor (see the two pages of discussion in Section 1.40 about "REMARKS ON OPENING ACTION"). There are pathological cases where the trapezoidal rule gives answers that oscillate around the true value, so that this remedy is useful.

1.0e5 Request for Allocation of Total TACS Storage

TACS is the control-system modeling feature of Section 8. Total working space for all TACS tables is assigned in List 19, along with the other 24 or so EMTP lists (see Section 0.6). But there still remains the question of how this total working space is to be divided among the 15 TACS tables. This allocation is performed at execution time, according to the description of the present section, thanks to the procedure of offset subscripting (see Ref. 8, Vol. VIII, 27 January 1979, page PROV-19 through 22).

The first way to allocate total TACS storage is with a request for absolute TACS table sizing, followed by two data cards giving those desired sizes:

ABSOLUTE TACS DIMENSIONS

LT_1	LT_2	LT_3	LT_4	LT_5	LT_6	LT_7	LT_8	LT_9	LT_{10}
LT_{11}	LT_{12}	LT_{13}	LT_{14}	LT_{15}					

The format for the list sizes is (10I8), with the 15 TACS table sizes having the following meaning:

LT1 : Maximum number of TACS dynamic function blocks, having Laplace transfer functions H(s) .

LT2 : Maximum number of zero-th order TACS function blocks (having type-code 0 or 99 punches in columns 1-2).

LT3 : Maximum total number of input variables to TACS dynamic function and zero-th order blocks.

LT4 : Maximum number of TACS sources. This includes built-in sources (e.g., "TIMEX" or "UNITY"), and variables passed from the electric network to be TACS driving functions.

LT5 : Maximum number of supplemental variables and devices (type codes 99, 98, or 88 punched in columns 1-2).

LT6 : Maximum total number of arguments of all supplemental variables (not supplemental devices).

LT7 : Maximum total number of numeric (not ALPHANUMERIC) arguments of TACS supplemental variables (not supplemental devices).

LT8 : Maximum number of TACS supplemental devices (Type codes 50, 51, ... 58).

LT9 : Maximum total number of signed input variables to supplemental devices.

LT10 : Maximum total number of TACS transport delay history terms, plus TACS digitizer levels, plus twice the number of points for TACS nonlinear characteristics.

LT11 : Let $N(i)$ be the dynamic order of the i-th dynamic function block. Then LT11 is the maximum of $N(i)+1$ summed over all dynamic function blocks "i" .

LT12 : Maximum total number of dynamic and zero-th order TACS function blocks. Note: LT12 may be less than the sum of LT1 and LT2 .

LT13 : Maximum number of distinct 6-character alphanumeric names used in the TACS data specification.

LT14 : Maximum number of nonzero factors of the triangularized TACS network matrix. This limit applies to both the steady-state solution and the transient solution.

LT15 : Maximum number of TACS output variables (as requested by the user immediately before TACS initial condition cards).

Provided the total storage represented by this user request is less than or equal to the List 19 space available, execution will proceed normally. If not, the fact will be noted upon entry into "TACS1" of overlay 1 (which occurs after reading of the "TACS OUTPUTS" card of section 1.id), and execution shall be stopped with a KILL = 1 EMTP error message pointing to List 19 .

The second way to allocate total TACS storage is with a request for relative sizing. That is, rather than request a specific number of function blocks, supplemental variables, etc., one can simply request a proportional allocation (e.g., 5% of the total storage for function blocks, etc.). There first is the special-request card, then the two data cards bearing the 15 proportions:

RELATIVE TACS DIMENSIONS

K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	K_9	K_{10}
K_{11}	K_{12}	K_{13}	K_{14}	K_{15}					

But one problem with this second option is that the user has no intuitive feel for the relative space taken by different tables. To aid the user, we present an approximate correspondence between nominal absolute dimensions and the proportions which produced them:

This applies to translations having integers which are half as long as floating-point and ALPHANUMERIC variables (INTEGER*4 vs. REAL*8 for IBM, PRIME, VAX, SEL). Proportions are a little different for computers where floating-point variables are the same length as integers (CDC; also single-precision translations for Univac and Honeywell).

In the absence of either such special request card for TACS dimensioning, the EMTP sets dimensions according to the following default absolute dimensions:

```
          10   10   50   20   30   50   30   20   50  100
          30   20   60   90   18
```

Depending upon the size of List 19 , execution may or may not be possible (i.e., even with default dimensioning, there still might not be sufficient table space for execution).

Diagnostic printout creates a special problem, as it was not variably-dimensioned along with the production output. It will only work correctly on computers having integers which are half as long as floating-point and ALPHANUMERIC variables (INTEGER*4 vs. REAL*8 for IBM, PRIME, VAX, and SEL; INTEGER*3 vs. REAL*6 for Harris). Further, the default dimensioning of one paragraph above must be used (i.e., there must be no "ABSOLUTE/RELATIVE TACS DIMENSIONS" cards).

1.0e6 Request for Combination and Tabulation of "STATISTICS"

Provided the user has previously executed a "STATISTICS" data case one or more times beforehand, and saved the essential internal tables (using "STATISTICS OUTPUT SALVAGE" request of Section 1.0e7), then it is possible to proceed with the statistical tabulation of overlay 29. This begins with a special-request card reading:

```
1234567890123456789012345678901234
TABULATE ENERGIZATION RESULTS
```

At this point, program control is transferred to overlay 29, where the 3-digit integers that uniquely identify all previous simulations (see parameter JFLSOS of Section 1.0e7) are specified:

I8	I8	I8	I8	I8	I8	I8	I8	I8	I8
JF_1	JF_2	JF_3	JF_4	JF_5	JF_6	JF_7	JF_8	JF_9	JF_{10}

Use as many cards as desired, skipping any of the 8-column data fields if this is convenient. Ordering of the integers is immaterial. Signal the end of such data by punching "9999" in a field to the right of the last real integer specification.

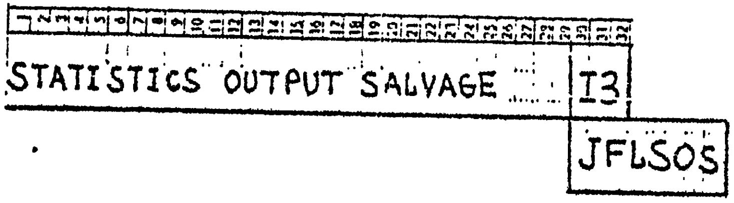
That is all that can be said for the data input. This constitutes the end of data for such a data case. After this universal data input in "SUBR29" is accomplished, installation-dependent module "STATRS" of overlay 29 is called, once for each partial simulation which is now to be tabulated. Module "STATRS" actually attaches (connects) the associated disk files, and reads the data into internal program storage.

Refer to installation-dependent instructions of Section 0.5a onward for the computer system of interest, for further details as to file identification, special complications for a particular system, etc. If nothing is found there, the curious user might study a listing of "STATRS" , and have a talk with local program maintenance, should there be trouble.

1.0e7 Request for Saving of "STATISTICS" Tables for Later Tabulation

Because "STATISTICS" data cases can be so time consuming, it is often convenient to solve them in pieces. Take a really big case (either many nodes, or many time steps, or both), which might require 15 minutes for the base case simulation. If 100 shots of "STATISTICS" simulation were desired, it would be an all-day operation --- with a good probability of a computer crash in the interim, which would lose everything. Also, when one so puts his eggs all in one basket, yet can not look at the output until the job is complete, it is not unheard of for a user to waste the entire output due to input data errors. Much more prudent is the splitting of such a large job into a number of smaller ones (e.g., five jobs of 20 shots each), solve the smaller jobs individually, and then combine and tabulate results later using the "TABULATE ENERGIZATION RESULTS" feature of Section 1.0e6 .

For most computer systems (those which catalog files before any data is written), the following special request card is required for the saving of "STATISTICS" results for later tabulation:



The 3-digit integer field JFLSOS allows the user to identify the disk files which result using a decimal serialization between 001 and 9999. If JFLSOS is left blank or punched with zero, the EMTP shall itself generate such integer identification randomly. The only disadvantage with this is that then the user does not know file names before the case has been solved (the random serialization will appear in the column 1-50 interpretation of the "STATISTICS OUTPUT SALVAGE" data card).

So much for the universal aspects of file identification. The three decimal digits are typically appended to the end of some standard root word, to create actual system file names. As such file naming is system or installation-dependent, the user is referred to instructions for his system which begin with Section 0.5a , or to his local Program Maintenance. He might also look at the FORTRAN coding of "MIDOV1" of overlay 1, where file opening should be placed (see also Section 0.5).

For those computer systems which can catalog files after they have been written (e.g., EMTP exploitation at the BPA CDC-6500, using special customized software), there is more flexibility. The just-described request card can either appear at the beginning of the data case as just described, or at the very end, positioned so as to be read as the first data card of the following data case. In this position, it is read in overlay 55, before the printout of the case summary statistics. Even if the job bombed off for some reason on the BPA CDC-6500 the EMTP would regain control from the operating system (provided the system itself had not crashed), and would save the relevant "STATISTICS" files by a call to installation-dependent module "STATSV" of overlay 55. But this is the exception rather than the rule. Systems as nice as this do not seem to be built any more (those were the good old days, when it came to salvaging "STATISTICS" simulations)!

1.0e8 Request for Omission of Base Case of "STATISTICS" Simulation

The conventional "STATISTICS" or "SYSTEMATIC" data case i involves a base case solution before any of the NENERG (integer miscellaneous data parameter; see Section 1.0h) energizations are begun. This is a preliminary shot right down the middle, with all of the variances set to zero. Well, the user can suppress this extra, preliminary simulation by a special request card reading:

```
OMIT BASE CASE
```

Resulting statistical tabulations are unaffected, since the base case solution was not part of the statistical processing anyway. So, if the user already knows what the base case solution looks like, he can save one shot, as well as some paper. A classic case is where one is solving one of several small pieces of a bigger problem, using "STATISTICS O OUTPUT SALVAGE" as in Section 1.0e7 . It would be wasteful and unnecessary to repeat the same base case solution for each piece of the problem that is solved.

1.0e9 Request to Read Miscellaneous Data Cards

The floating-point and integer miscellaneous data cards are d described in Section 1.0h . For a conventional simulation, they come after all special requests of the type now being considered. For the normal simulation this is fine, and there is no problem.

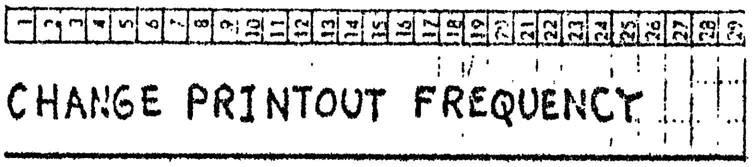
But in special circumstances, the user may want to define one or more of the miscellaneous data parameters ahead of time. Perhaps I should not say "ahead of time," since in the extreme case where there is no simulation at all (e.g., when using "LINE CONSTANTS"), such data cards would otherwise never be read. Anyway, the user can have miscellaneous data cards of Section 1.0h read at this time provided he precedes the cards by the appropriate special-request word:

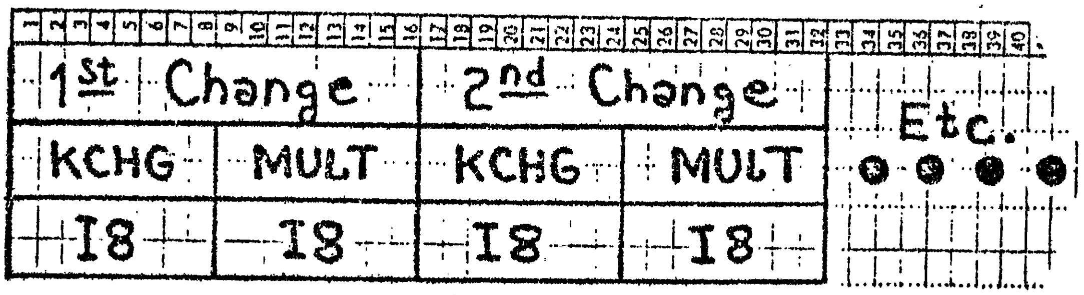
```
MISCELLANEOUS DATA CARDS
10E8.0 ~ floating point miscellaneous data card
10I8   ~ integer miscellaneous data card
```

The user is advised not to do this casually, however; there should be a real known need, and local Program Maintenance should be aware of the usage.

1.0e10 Request to Change the Frequency of Time-Step Loop Printout

Printout in the time-step loop has frequency controlled by integer miscellaneous data parameter IOUT of Section 1.0h . But this frequency can be changed as simulation time progresses. Begin with the special-request card shown at the right, and follow this with the card of (KCHG, MULT) pairs of Section 1.1b :


CHANGE PRINTOUT FREQUENCY



1st Change		2nd Change		Etc.
KCHG	MULT	KCHG	MULT	● ● ● ●
I8	I8	I8	I8	

This card specifies at what time-step numbers the printout frequency is to be changed, and what values the frequency is to be changed to. Up to five pairs of step numbers and new printout frequencies are permitted, as per the following definitions:

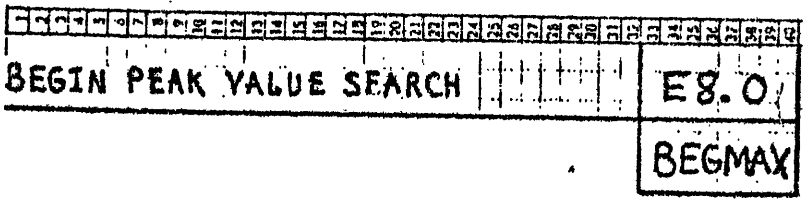
$KCHG_i$ ------ Time-step number at which the i-th variation in the printout frequency is to begin. Printout for this particular step number is always provided, as a beginning to the new frequency of output.

$MULT_i$ ------ Modified value of "IOUT" (see second misc. data card), to begin at time-step number $KCHG_i$.

A change in the printout frequency was originally provided as per Section 1.1b , if integer miscellaneous data parameter IPUN was given a value of minus one. That still applies. But IPUN also has meaning when it is positive: the punching of terminal conditions. The user may want to do both of these operations in the same data case, which was impossible before (variable IPUN could not be both negative and positive at the same time). The special request card of the present section resolves this potential conflict. Users may prefer it even if there is no conflict.

1.0e11 Request for Delay in Extrema Calculation

The integer miscellaneous data parameter MAXOUT (see Section 1.0h) provides for the calculation and output of variable extrema. The same vector of extrema is used for "STATISTICS" and "SYSTEMATIC" output as well. Normally, extrema are wanted over the full time span of the simulation. But not always. There are cases where one wants to ignore a certain initial interval of the simulation, only considering transients after a certain minimum time. For example, in a ""STATISTICS" simulation, it is possible that random closing shall follow the opening of breakers (clearing of a fault), but that the peak simulation voltage will be produced during the deterministic opening portion of the simulation. If extrema were calculated over the whole time span of the simulation, each energization would generate identical peaks, which is useless to the designer. So, in this case, the solution is to inhibit the calculation of extrema until transients of the opening phase of execution have passed. This is possible, using a special-request card which reads as follows:

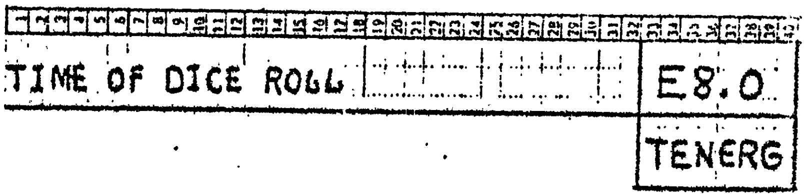


Here BEGMAX is the time in seconds at which the extrema computation is allowed to begin.

1.0e12 Request for "STATISTICS" Table Saving at a Specific Time

As explained in Section 1.40, Class 3a, a "STATISTICS" data case can involve the random opening of switches (rather than the more conventional random closing). The development of this capability is documented in Ref. 8, at the end of Vol. IX, 6 November 1979, page EOVN-1 and 2 . Had there been sufficient time to develop this option, there would be no need for the special request of the present section. The special-request that is now to be described really just represents a patch; if EMTP tables are straightened out at some later date, it should be removed.

Well, if the user wants to manually define the simulation time at which the EMTP tables are to be saved, so that each energization need not repeat the deterministic simulation up to this point, he uses the following special-request card:



Variable TENERG is in /BLANK/ , and it is the time before which no random switching can reasonably occur. If this variable is set equal to -FLTINF in installation-dependent module "SYSDEP" of overlay one (see Section 0.5), which is the VAX and Univac usage as of March 1980, then we have the following cases:

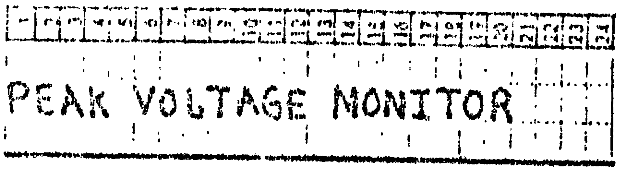
1. If a "STATISTICS" or "SYSTEMATIC" data case is executed without a "TIME OF DICE ROLL" special-request card with reasonable positive TENERG , then internal program table dumping will be at time zero. This is done in overlay 15, at the end of "OVER15" , by the call to TABLES . In this case, the deterministic portion of each energization is repeated for each random simulation. THIS IS REQUIRED FOR THE CASE OF ONE OR MORE RANDOMLY-OPENING SWITCHES, due to the aforedescribed sloppy table housekeeping. But it is wasteful and unnecessary if there are no random-opening switches.

2. If the "TIME OF DICE ROLL" card is present in a "STATISTICS" or "SYSTEMATIC" data case, then the user defines the time at the end of the deterministic portion of all simulations at which tables can be saved. As long as there are no random-opening switches, do this, to save computer time (if TENERG is a significant fraction of TMAX).

Current (March, 1980) thinking is that all program versions to be set up during the summer of 1980 shall be this way. But there may be exceptions. The key point is the initialization of TENERG within "SYSDEP" . If that negative initialization is not present, then the above does not apply. Instead, TENERG is automatically defined internally. This is fine for the case of just random closing, in this way sparing the user from defining the table-saving time himself manually. But then the random-opening case is fouled up, if the user fails to disable the automatic procedure by inputting a special-request card with TENERG negative. This would be a disaster (wrong answers to the simulation), and it is to guard against this worst case that the options of the preceding paragraph were decided upon. If there are questions about this, or if the second alternative are desired (e.g., if random opening will never, ever be used), contact Program Maintenance.

1 0e13 Request for Peak Node Voltage of Simulation

For the user who is interested in peak node voltage, but is not sure at which node this will occur, we have the paper-saving alternative requested as shown to the right:



PEAK VOLTAGE MONITOR

Then, at the end of the simulation, before the usual peak-value printout for the output vector, will be generated one line of output from the following statements:

```
         WRITE (LUNIT6, 5011)  PEAKND(1), PEAKND(2), BUS(N6)
    5011 FORMAT ( 6X,  38HOVERALL SIMULATION PEAK NODE VOLTAGE =,
       1  E15.6,       17H .  TIME (SEC) =,
       2  E14.5,       12H .  BUS = ',    A6,    3H' .     )
```

Remember that this is the peak node voltage in volts, not in per unit. If the problem has transformers which step the voltage up or down, there is no way of spotting per unit peaks which might occur on the low voltage side.

1.0e14 Request for Allocation of Total U.M. Storage

The universal machine (U.M.) component of Section 1.63 has total working space for all tables assigned in List 25 of the overall program variable dimensioning (see Section 0.6). But there still remains the question of how this total working space is to be divided among the four U.M. tables. This allocation is performed at execution time, according to the description of this section, thanks to the procedure of variable dimensioning by arguments of a SUBROUTINE call (see Ref. 8, Vol. I, 3 July 1974, page VDTP-2 onward).

The first way to allocate total U.M. storage is with a request for absolute U.M. table sizing:

ABSOLUTE U.M. DIMENSIONS	I8	I8	I8	I8
	NCLFIX	NUMFIX	IOTFIX	IBSFIX

NCLFIX (33-40)	-----	Maximum total number of U.M. coils in the data case. This is the total for all U.M. components involved.
NUMFIX (41-48)	-----	Maximum number of U.M. components for the data case.
IOTFIX (49-56)	-----	Maximum number of U.M. output quantities (total for all machines).
IBSFIX (57-64)	-----	Maximum number of U.M. 6-character alphanumeric names (total for all machines).

Provided the total storage represented by this user request is less than or equal to the List 25 space available, execution will proceed in a nominal fashion. If not, this fact will be noted by module "UMOFFS" of overlay 5, as the first U.M. data component itself is ready for input, and an EMTP error stop will result. In any case, the corresponding minimum size for List 25 will be printed out by "UMOFFS" as part of the column 1-50 interpretation of the Type-19 request card for U.M. modeling. This way the user knows what fraction of the available space he is utilizing.

The second way to allocate total U.M. storage is with a request for relative sizing. That is, rather than request a specific number of coils, machines, etc., one can simply request a proportional allocation (e.g., 50% of the total storage could go for coils, etc.). The format for such an allocation is:

RELATIVE U.M. DIMENSIONS	I8	I8	I8	I8
	JNCL	JNUM	JIOT	JIBS

We still use integers, note; and the four data fields correspond one to one with the four tables as described for "ABSOLUTE U.M. DIMENSIONS", but here the meaning is a fraction of total available space for that table. In order to use this effectively, one must know the multiplicity of the four tables:

REAL	4	17	0	0
INTEGER	4	12	2	0
ALPHANUMERIC	0	0	0	1

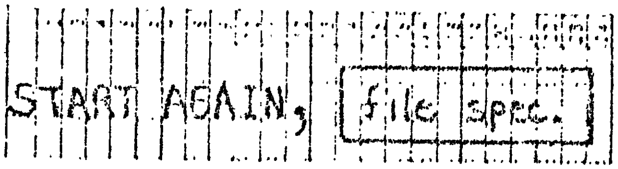
For a computer with half-length integers (e.g., IBM, VAX, PRIME, and SEL, all of which use REAL*8 and INTEGER*4 translations), the overall byte weighting is: (6, 23, 1, 1) . On the other hand, for a word machine where variables all have the same length (e.g., CDC), the overall word weighting is: (8, 29, 2, 1) . Using which ever of these is appropriate, multiply the corresponding absolute dimensions by these components in order to produce the corresponding relative dimensions.

As an example of this, suppose that absolute dimensions that are deemed to be balanced are the default ones of the EMTP : (20, 3, 50, 60) . Well, operating at BPA on our VAX, the weighting (6, 21, 1, 1) then produces the associated relative dimensions (120, 69, 50, 60) . If the data card "RELATIVE U.M. DIMENSIONS, 120, 69, 50, 60" were then placed at the top of a data deck with involved U.M. modeling, these numbers would never have to be altered, no matter how many machines were involved. Of course, if there were too many machines for the available memory, there would be an overflow error stop. But this could be corrected by redimensioning the EMTP with larger List 25 , without touching the RELATIVE U.M. DIMENSIONS card.

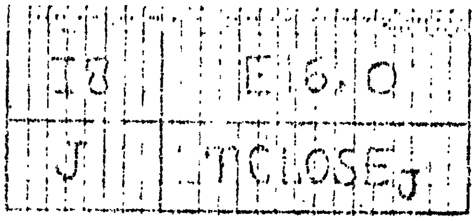
If the user fails to input one or the other of the above two cards which specify U.M. table sizing, then the EMTP allocates absolute dimensions in "UMOFFS" of overlay 5 which equal (20, 3, 50, 60) . These, then, are default dimensions. For IBM, VAX, PRIME, and SEL, a List 25 size of 300 is sufficient for this usage (and it corresponds to the default allocation of VARDIM for List 25). Word machines will need more (my calculations show that 410 should do the job).

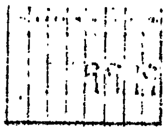
1.0e15 Request to Restart a Halted Simulation

Integer miscellaneous data parameter MEMSAV will result in the dumping of EMTP memory onto disk at the conclusion of a simulation (i.e., at t = Tmax). For those computer systems which have allow this capability, such a simulation can be restarted, as documented in Ref. 8, Vol. X, pagination MSDO, 3 July 1980. Also see the following memo, which contains modifications. In the present material, it shall be shown how such a halted simulation can be restarted using the "START AGAIN" request.



The request to load those memory contents back from disk is of the form shown at the right. The request-word "START AGAIN" is univeral, but the file specification which follows will depend upon the computer system being used. Indeed, there may even be more installation-dependent information on this data card; consult the instructions pertaining to your computer version at the front of the manual before going further.



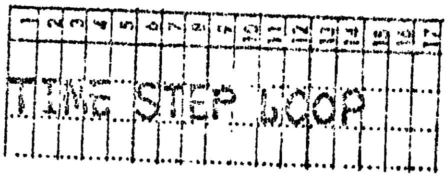


The just-described request is to be followed by an arbitrary number of cards which redefine switch closing times Tclose , terminated by a 9999-card (in columns 5-8). See formats at the right. Here "J" is the switch number, in order of data input. As a general rule, only time-controlled switches which are open at the end of the halted run can be so modified. After this data, TMAX can be altered with a "MISCELLANEOUS DATA CARDS" request of Section 1.0e9, and then a "TIME STEP LOOP" request of Section 1.0e16 actually transfers control to the time-step loop to begin again the simulation.

A few additional points might be passed along as well. Between the "MISCELLANEOUS DATA CARDS" and the "TIME STEP LOOP" requests, the user is able to place any other special requests which seem appropriate. The most commonly used is "CHANGE PRINTOUT FREQUENCY", to alter the frequency of the time-step loop printout. If this is done, remember that step numbers begin where the previous halted run left off (e.g., for TMAX = 50 msec and DELTAT = 100 microsec, the first printed step would be for number 500). Yet the user should be aware that, while all requests may be accepted by the EMTP, some of the more complex ones can not possibly be honored in fact. Perhaps the best example is "RENUMBER BYPASS" of Section 1.0g4 ; since renumbering is to be skipped (control is transferred immediately to the time-step loop), there is no way node renumbering can be altered. Even worse are some requests which will simply make erroneous or inconsistent certain parameters of the memory contents to be restarted. An example of such a potential disaster is provided by use of the "ABSOLUTE TACS DIMENSIONS" request of Section 1.0e5 . Use of this feature would alter the pointers to the TACS tables, without changing the tables themselves (which are already built), leading to "garbage in", and most likely an operating system interrupt of some sort. Hence the user is warned to be both intelligent and skeptical about any such usage; if there are some added hidden benefits, there also are some very real limits, and some hidden traps. Be cautious!

1.0e16 Request for Transfer to the Time-Step Loop

Used in conjunction with the "START AGAIN" request of Section 1.0e15 , the appearance of the "TIME STEP LOOP" card will begin execution by a transfer of control to the time-step loop.



1.0e17 Request for Postprocessing of Plot File Using TACS

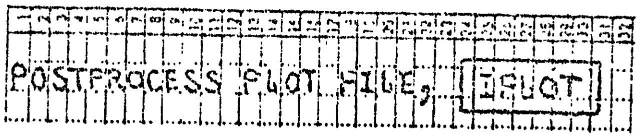
TACS can be used for the postprocessing of plot files, as described in Ref. 8, Vol. X, 3 July 1980, page MSDO-6. Yet the user is cautioned that this is installation-dependent, and will work only for those computer systems which honor a $OLDFILE request (logic built into module "CIMAGE").

For so-equipped program versions, the procedure is summarized as follows. First connect the old plot file (input to the post processor) to LUNIT2 using $OLDFILE :

$OLDFILE, [plot file specification] , [LUNIT2]

Note that exact formats can not be indicated, due to the installation-dependent nature. Users should consult the specific information for their computer systems (Section 0.5a onward). As for LUNIT2 , this is to be the I/O unit number that is assigned to variable LUNIT2 . This will be 2 unless a system-dependent assignment within module "SYSDEP" alters the natural assignment. Variables in this plot file will be assigned to user-defined TACS sources in natural order by the EMTP, thereby providing the connection for postprocessing by the user.

Next comes the key request, as shown at the right. This is a universal card. Here "IPLOT" is to be an integer indicating frequency of the output, not unlike the miscellaneous data parameter of the same name. For example, if IPLOT = 3 is used, then only every third point of the old plot file shall be used. The most common (and least tricky) case is for IPLOT = 1 , so that there are as many output points as there are input ones.



```
POSTPROCESS PLOT FILE, IPLOT
```

The data case is completed by cards for a TACS-only (TACS STAND ALONE) EMTP data case. There are generally to be as many TACS sources as there are variables in the old data file, with 6-character names being arbitrary. In the order defined, these are automatically (internally) connected to variables of the old plot file. Most post-processing will involve supplemental variables, though function blocks are also useful (e.g., 1/S for integration of voltage to give flux).

1.0f Input Karrenbauer Mode-Voltage Output Request for Distributed Line

There are cases where mode-voltage rather than phase-voltage output is desired, generally for educational usage of one form or the other. Now, distributed-parameter transmission line modeling of Section 1.26 uses the Karrenbauer transformation to decouple the multi-conductor line equations, so such modal output is quite natural, and easily provided. With care, the user can request the Karrenbauer components of voltage to ground at both ends of one distributed-parameter transmission line, as shall be described shortly. Refer to Section 4.1 for a definition of the transformation in question, including specification of the natural order of the modal variables therein.

First, before input of the miscellaneous data cards of Section 1.0h, the user must declare his desire for modal (voltage) output by means of the following special request card:

MODE VOLTAGE OUTPUT	MODOUT
	I2

Cols. 1-19 : Enter the special request word "MODE VOLTAGE OUTPUT" .

Cols. 33-40 : Enter the number of phases (or coupled conductors) which make up the distributed-parameter line whose modal output is desired. A blank or zero field will be given default value equal to 3 , which is the most common case, of course.

Such a special request card can be preceded by a "BEGIN NEW DATA CASE" card, and either preceded or followed by parameter-redefinition cards of Section 1.0c, if desired; comment cards can also be mixed in anywhere, of course (using "C " in columns 1 and 2).

Additional data-input obligations and/or constraints on the user of this feature include the following:

Point 1 : The distributed-parameter transmission line in question (for which the user wants mode voltage output) must be the final branch-component of the data case; it must immediately precede the blank card which terminates all branch cards.

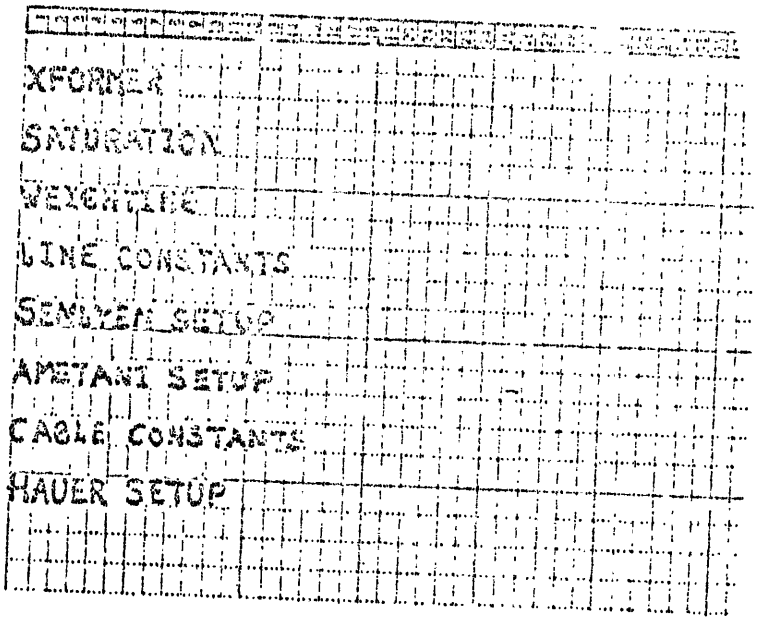
Point 2 : The very first branch data of the data case should consist of fictitious high-resistance branches from each node at both ends of the line in question to ground. Equal in number to 2 * MODOUT , column 80 of these uncoupled (type-zero) resistive branches must be punched with a 1 so as to request branch-current output. Use a resistance value which is so large that the problem is unaffected by addition of these resistors (see Section 1.2! for acceptable limits on different computer systems).

95

So much for data input. After the case has been run, the user will find his Karrenbauer mode voltages in the output locations which should otherwise have been reserved for the branch currents of Point 2 above. This is way the present feature is a little tricky. The first "MODOUT" output currents are in reality Karrenbauer mode voltages to local ground at the "BUS1" end of the line, in natural order; the next "MODOUT" output currents are mode voltages to ground at the other end ("BUS2" end) of the line, also in natural order. A reminder message to this effect is printed immediately below the column headings for the output variables, so the user will not forget. Note that if one is plotting, type-9 plot requests (see Section 1.10) must be used, since the EMTP thinks that the modal voltages are currents in the 2 * MODOUT high-resistance branches which were supplied by the user.

1.0g Special Requests for Transfer to Auxiliary Supporting Programs

Several programs are not part of the EMTP simulation process proper, but are sometimes used in order to compute parameter values which are needed for the setup of a data case. These separate calculation procedures have been appended to the EMTP as "auxiliary supporting programs", access to which is controlled by key request words. Section 7. describes the auxiliary supporting programs which are available, with the following being a list of the associated key words which are used for access:



XFORMER
SATURATION
WEIGHTING
LINE CONSTANTS
SEMLYEN SETUP
AMETANI SETUP
CABLE CONSTANTS
HAUER SETUP

A data case to use one of these auxiliary supporting programs then has the following structure:

1. First, a "BEGIN NEW DATA CASE" card, if desired (optional).
2. Then a card bearing the correct, desired special request word (see above list).
3. Finally, data for the auxiliary supporting program in question. This is completely described in Section 7. and thereafter.

1.0g1 Declaration of Intention to Use Analytically-Defined Type 1-10 Sources

As explained in Section 1.6, source types 1 through 10 are reserved for functions which are directly defined by the user. If one or more such source functions is to be defined in FORTRAN within a special user-supplied version of subroutine "ANALYT" , then the following special request record must precede input of the miscellaneous data cards for the data case in question:

```
ANALYTIC SOURCES USAGE
```

It is the user's responsability to see to it that his own special module "ANALYT" has replaced the dummy one which comes with the program, when actually executing a data case which contains such an "ANALYTIC SOURCES USAGE" request.

1.0g2 Declaration of Intention to Use TACS-Defined Type 1-10 Sources.

As explained in Section 1.6, the source types 1 through 10 are reserved for functions which are directly defined by the user. If one or more such source functions is to be defined within TACS as a signal whose value is determined by the user-defined TACS data, then the following special request card must precede input of the miscellaneous data cards:

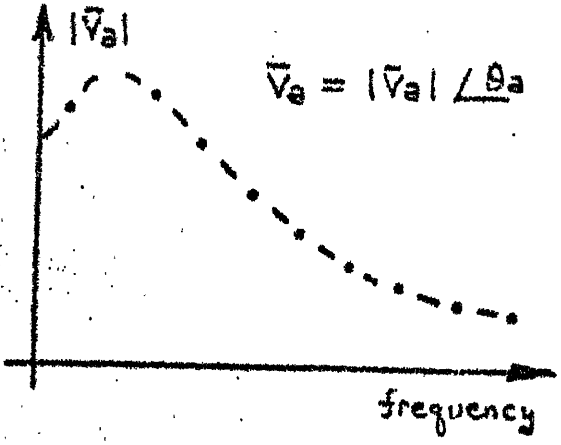
TACS EMTP SOURCES	A6	A6	A6	A6	A6	A6	A6	A6	A6	A6
	1	2	3	4	5	6	7	8	9	10

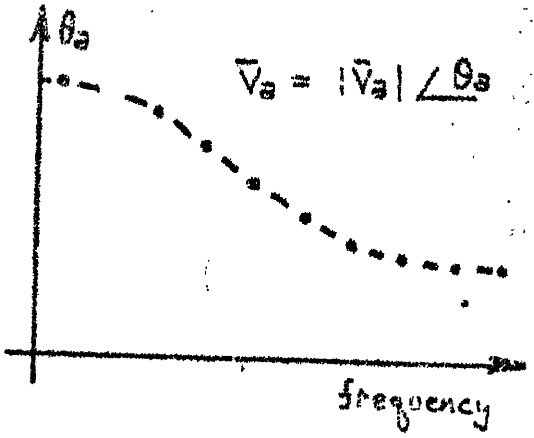
Names of TACS variables which control electric network sources having type-codes 1-10

First, the special text "TACS EMTP SOURCES" is to be punched in columns 1-17 of the card. Then, if an EMTP electric-network voltage or current source of type-code number K (for K between one and ten) is to be controlled by TACS, the 6-character name of the controlling TACS variable is to be punched in the K-th name-field of the card. Of course any such name punched on this card must be defined as part of the TACS data specification of Section 8. • (See also simpler source type 60-99 in Section 1.6)

1.0g3 Declaration of Intention to Use the "FREQUENCY SCAN" Feature

The "FREQUENCY SCAN" feature of the EMTP allows for the repetition of steady-state phasor solutions, as the frequency of sinusoidal sources is automatically incremented between a beginning and an ending frequency. Rather than conventional EMTP time-response output, the user then has available a frequency-response output. When plotted, the time axis of conventional EMTP simulations becomes the frequency axis, with the result being a Bode plot. Polar coordinates (magnitude and angle of the phasor solution variables) are used for output purposes. For example, the following could apply to the node voltage of phase "a" somewhere in the network:





Should the user desire to make a "FREQUENCY SCAN" simulation, then the following card must precede input of the floating-point miscellaneous data card:

FREQUENCY SCAN	E8.0	E8.0	E8.0	I8
	f_{min}	Δf	f_{max}	NPD

f_{min} ——— Beginning (minimum) frequency of the scan, in Hertz. This must be a positive number.

Δf ——— The frequency increment, if the user wants uniform spacing between adjacent frequency points. In this case, $f_{k+1} = f_k + \Delta f$. If logarithmic (geometric) spacing between adjacent frequency points is desired, this field should be left blank.

f_{max} ——— Terminal or end (maximum) frequency of the scan, in Hertz. This must be greater than or equal to f_{min} .

NPD ——— For uniform spacing of the frequency points, leave this field blank. But if logarithmic (geometric) spacing is desired, this field is to be punched with the desired number of points per decade. In this case, adjacent frequency points are related by

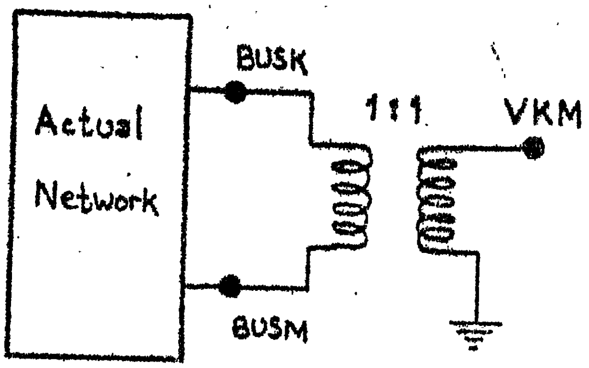
$$f_{k+1} = (10^{1/NPD}) \cdot f_k$$

Special attention should be paid to integer miscellaneous data parameter "KSSOUT" , when using the "FREQUENCY SCAN" option. See the Section 1.0h definition. If punched with unity, the full steady-state branch flow and injection printout will result, for each solution frequency of the scan. This could produce large quantities of printed output, if the number of frequency points is large. Be careful (save a tree in Oregon)!

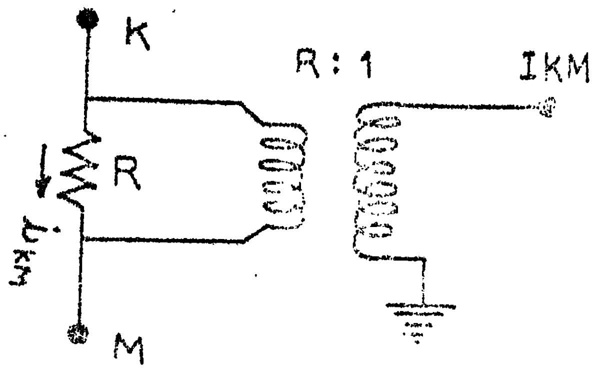
Except for the just-mentioned full branch-flow and injection printout, only node-voltage output is presently provided for "FREQUENCY SCAN" data cases. Any column-80 punches for branch or switch currents, voltages, powers, and energies will be disregarded by the EMTP. Node voltages are outputted in polar form, with the magnitude preceding the angle (which is in degrees). The printed output vector for each frequency* is composed of such pairs of real values, in the order that node-voltage outputs are requested by the user. The frequency in question precedes the first node-voltage magnitude, as the first output quantity of the vector. The step number and associated frequency are also printed as a heading which precedes the output vector (see example on following page).

For EMTP plotting purposes, the node voltages are actually classed as Type-9 variables. This allows for the identification of each variable by a pair of 6-character alphanumeric names, note. The first is internally generated by the EMTP ---- either "MAG " for the magnitude, or "ANGLE " for the angle; the second name is the name of the node in question. For logarithmic frequency spacing (variable "NPD" positive), it is actually the base-ten logarithm of frequency which is written onto the file of plot points, rather than frequency itself. Frequency (or the logarithm of frequency) then replaces time as the independent variable for plotting purposes, note. Appropriate labeling of the frequency axis is made by the choice of column-4 punch on the plot card.

If the user needs branch currents, or voltage differences, he is of course free to add one or more measuring transformers for this purpose. See Section 1.25 . A 2-winding transformer which draws no magnetizing current and has small leakage impedance should of course be used, to ensure accurate measurement (just as in the real world of instrumentation). For a voltage difference, the primary would be connected across the two desired nodes; the turns ratio would be unity, and the secondary would be left open circuited, with one terminal grounded. See sketch at right.



The just-described sampler of voltage difference can be easily extended to measure current. If nodes "K" and "M" are the terminals of a resistor which carries the desired current, then the measured voltage will equal the current if one uses a turns ratio of R : 1 (see sketch at right).



1.0g4 Request for Bypass of Transient Network Renumbering

Sparsity-based node renumbering is normally used on the coefficient matrix [Y] of the time-step loop. As per Scheme 2 of Reference 4, nodes are thus renumbered so as to preserve sparsity during the triangular factorization of [Y].

But, the just-described transient node renumbering can be bypassed (omitted) if so desired, by means of the following special request card which must precede the miscellaneous data cards:

```
RENUMBER BYPASS
```

In such a case, nodes will remain numbered in the order that they will be encountered upon the reading of EMTP branch data. On any one branch card, it is the left node (data field "BUS1" of columns 3-8) which is processed b fore the right node (data field "BUS2" of columns 9-14).

Actually, more than just a bypass of transient network renumbering is involved. By agreement, the full [Y] is to be retriangularized whenever [Y] changes (e.g., when a switch changes status). Switch nodes and pseudononlinear element nodes are no: necessarily eliminated after unknown voltage nodes which are not in this class, note. There is no partition-A triangularization outside of the time-step loop in this case. This is the whole rationale behind the use of the "RENUMBER BYPASS" feature ——— there is no artificial forcing of switch and pseudononlinear-element nodes toward the bottom of the matrix.

Use of the "RENUMBER BYPASS" feature is not recommended for beginners. In fact, its use by even old hands is rare, and is recommended only for very special big problems. One such example is a full ac/dc converter representation which might require 50 or 100 EMTP switches to represent the valves.

1.0g5 Specification of Changes in Time-Step Size

The size of the time-step "DELTAT" can be altered during the course of a simulation, by special request. The floating-point miscellaneous data card (see Section 1.0h) only specifies the initial value of the time step, which is to apply at the beginning of the simulation. Thereafter, "DELTAT" can be altered at will by the user, by means of the following special-request cards which must precede input of the miscellaneous data cards:

First : Begin with a card which has the text "MODIFY DELTAT" punched in columns 1-13 :

```
MODIFY DELTAT
```

Next : For each instant of simulation time that the step-size "DELTAT" is to be changed, the user is to supply a card which is punched in the following format:

T_i	DT_i	NPR_i	NPL_i
E16.0	E16.0	I8	I8

T_i ——— The next time instant at which a change in the step-size "DELTAT" is desired.

DT_i ——— The new time-step "DELTAT" which is to go into effect at time T_i .

NPR_i ——— The frequency of the printed output which is to be in effect after the i-th "DELTAT" change. A zero or blank field is taken to mean that no change in the printout frequency is desired (i.e., the frequency is to be held at whatever value was in effect just before the change). A value of -1 will suppress all subsequent printout (in effect, this corresponds to an infinite input value, note). Recall that the frequency of the printout will begin at the value specified by the integer miscellaneous data parameter "IOUT" (see Section 1.0h).

NPL_i ——— Like NPR_i , only for plotting rather than printing.

Such cards are to be arranged in order of strictly-increasing (monotone-increasing) T_i . There is no restriction on the first and last T_i values vis-a-vis the actual beginning time "TMIN" and the actual ending time "TMAX" of the simulation; the EMTP logic will simply ignore those requests for changes which do not occur within the "time window" of the simulation. The maximum number of permissible changes to "DELTAT" is fixed by EMTP dimensioning, and is not under user control. As of June 1977, a limit of eight was being imposed on users.

Finally : Indicate the end of the preceding cards by means of a special terminator record which has "9999" punched in columns 13-16 :

```
            9999
```

As an example of the preceding cards, consider a case in which "DELTAT" starts out as 100 microseconds on the floating-point miscellaneous data card. Two changes in this step-size could then be produced by records such as the following:

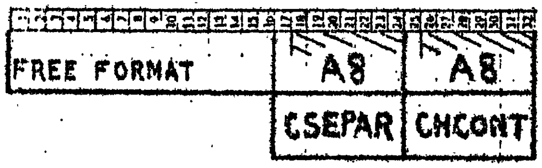
```
MODIFY DELTAT
        .0176              .000150       20       1
         .050              .000200       40       3
         9999
```

At 17.6 msec, the step-size is to be increased to 150 μsec, with the printout of every 20th point and the plotting of every point. Then at 50 msec, this is altered a second time, to a step-size of 200 μsec, a printout frequency of 40 and a plot frequency of 3 .

WARNING ! This feature is generally unusable, for the typical production EMTP data case. It is based on an automatic internal restarting using initial condition cards as described in Section 1.7 . But such capability does not exist as of today (April, 1980) for most sophisticated EMTP components. See the end of Section 1.7 . Hence one can not use "MODIFY DELTAT" for these cases. For this reason, it has never been used in the production mode at BPA. Ontario Hydro did find the feature useful (I believe for capacitor-bank switching studies, where only switches, sources, and R-L-C branches, and PI-circuits were involved) during 1979, and corrected one or more bugs associated with it at that time. Thus the current status can probably best be testified to by Russ Brierley and/or Dr. Vladimir Brandwajn (see section 0.5 for address and telephone number).

1.0g5 Re-Definition of Free-Format Data-Field Delimiters

As explained in Section 0.7 , certain classes of EMTP data may be punched either according to the conventional fixed-format specifications, or using the newer free-format option. This latter mode makes use of two special alphanumeric characters : one which separates data fields, and one which requests a continuation card. Should the user want to re-define one or both of these characters, a data card in the following format should be punched, and should precede the miscellaneous data cards:



CSEPAR ---- The single alphanumeric character which is to serve as separator between adjacent data fields. Punch this character left-adjusted in the field shown (i.e., in column 17). Mneumonically, the name signifies "Character SEPARator" . If left blank, a comma (",") will be assumed; if no such redefinition card is present, a comma will be assumed.

CHCONT ---- The single alphanumeric character which is to serve as a request for a continuation data card. Punch this character left-adjusted in the field shown (i.e., in column 25). Mneumonically, the name signifies "CHaracter CONTinuation" . If left blank, a "$" sign will be assumed. Remember that this must be a special character which the user will never employ as part of his non-comment EMTP data cards.

If the user wants all data cards of the data case in question to be read using fixed formats, he should enter "9" (nine) for "CHCONT" . By definition, this will bypass all attempts at free-format data reading (except for the free-format FORTRAN expression in TACS), and will thus speed up input slightly. It will also guard against possible confusion of the fixed-format data with free-format recognition rules.

As of April of 1980, the free-format option has been implemented for most EMTP data structures. But there are important exceptions, so it should be used with caution and considerable skepticism only.

The reason for incomplete implementation can be blamed on existing EMTP logic which uses two or more DECODEs of a data card image. For the first DECODE , which for EMTP usage typically begins at the left edge of the card, there is no ambiguity. But for the second and later ones, it is sometimes impossible or impractical to determine how many data fields have preceded it. EMTP logic simply is not so component-oriented (it is more table-oriented). The column-80 punch for branch current is a classic example, and my recollection is that this must remain as a fixed-format punch, even if the rest of the data card is free-format. Switch cards likewise suffer from this multiple-DECODE problem. There is no simple rule for knowing which data structures work with free-format usage, and it is impractical to tabulate an exhaustive list. I can only recommend skepticism and caution.

But an even more fundamental reason for not completing the free-format work is that the resultant data has been judged to have unacceptable reduced readability. For small data cases, this is not a serious problem. But with hundreds of data cards, where the user forgets the modeling details or even the extent, readability is most important. Column positioning of the nonzero data is an important element in allowing for the rapid visual scanning and interpretation of EMTP data cards. The counting of commas becomes impossibly slow and error prone (e.g., an inductor and a capacitor are distinguished by only one comma in a string of several). Yes, we need free-format capability for use with CRT terminals, but current thinking is that it will not be of the simple-minded type described in this section. One idea under consideration is that of data tags (see Ref. 8, Vol. IX, 6 August 1979, page FYTM-8, Project 2). Another idea is to write a special program which would assemble the fixed-format data records based on data which is supplied in various free-format pieces (thereby preserving readability for future use). Something will be done, though we are only talking about it today.

An important property of free-format numbers is that there is no distinction between integers and reals ("I" vs. "E" data fields). In fact, all numbers are extracted from the data card as reals, with a mode conversion subsequently used if the EMTP expected an integer.

The appearance of either "CSEPAR" or "CHCONT" characters (which have default values "," and "$" , respectively) on a data card is the sole determiner as to whether the card uses free format. Thus, it is imperative that these two characters not be buried in A6 names like bus names, or TACS variable names. As a general rule for staying out of trouble, I recommend that "CSEPAR" and "CHCONT" not be redefined without very good reason, and that users simply never use commas or dollar signs in A6 names. This assumes that the user has not disabled free-format capability (easily done within installation-dependent module "CIMAGE" ; see Section 0.5 for location), or that he does not always define "CHCONT" equal to "9" .

The summary recommendation from Portland is that users stay away from free-format usage, if possible. Being forced to enter EMTP data through a computer terminal is not a sufficiently strong reason for the use of free-format capability in the general case. All BPA data is so created, yet BPA production users still employ fixed-formatting. There should be a really overpowering reason, like the need for more precision, before it is recommended that the average user try his hand at free formatting. There simply are too many problem cases, too many things that can go wrong.

1.0g7 Request for Selective Diagnostic Printout

Parameter "IPRSUP" of the integer miscellaneous data card (Section 1.0h) will turn diagnostic printout on or off irrespective of the location of that printout within the program. That is, either all printout is turned on, or all is turned off, at a certain threshold level. If positive, "IPRSUP" will over-ride the selective printout request of this present section.

But if "IPRSUP" is to be punched zero or blank, then the EMTP diagnostic printout can be controlled overlay by overlay. A special-request card bearing the key word "DIAGNOSTIC" in columns 1-10 is used in this case. The following format is applicable for this card which must precede the miscellaneous data cards:

DIAGNOSTIC	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	(IPRSOV(I), I=1,30) ; I2 format																													

IPRSOV(K) ---- diagnostic printout control parameter as restricted to overlay number "K" . Within overlay "K" , IPRSOV(K) has the same meaning as "IPRSUP" as described in Section 1.0h .

For overlays "K" which exceed 30 , IPRSOV(K-30) is used to control the diagnostic printout. That is, only 30 distinct codes have been provided for, with these being reused cyclically for higher overlay numbers.

In the selection of these diagnostic-printout codes, special care should always be taken with regard to the time-step loop, which is overlay number 16 . Remember that diagnostic printout can be generated for each time step, so beware of the termination time "TMAX" in relation to the step-size "DELTAT" , should such printout be requested. Another consideration is for large networks, which will heavily impact on overlay number 7 (network node-renumbering). Here printout can be produced for each row of the matrix.

As a general rule, always consult with Program Maintenance if in doubt about the control of diagnostic printout. "Save a tree in Oregon."

Control of diagnostic printout for the time-step loop code of overlay 16 deserves further explanation. Actually, it is broken into four principal modules : SUBTS1, SUBTS2, SUBTS3, and SUBTS4 . Printout control parameter IPRSOV(16) applies to the first of these (SUBTS1), 17 applies to the second, 18 applies to the third, and 19 is for the last (SUBTS4). Since the time-step loop is followed by UTPF overlay number 20, there is no contradiction or confusion in this usage.

If diagnostic printout is being turned off and on as a function of time (see Section 1.1b, with a minus sign on MULT), then (IPRSOV(J), J=16, 19) alternate with (IPR(J), J=1, 4) for control of diagnostic printout of the time-step loop. There are two distinct cases:

Case 1: If the user wants to start with no diagnostic (Step zero or one), then IPRSOV(16) through IPRSOV(19) should all be zero, and the "ALTERNATE DIAGNOSTIC PRINTOUT" request of Section 1.0g8 should be used to define the nonzero printout codes (one or more nonzero).

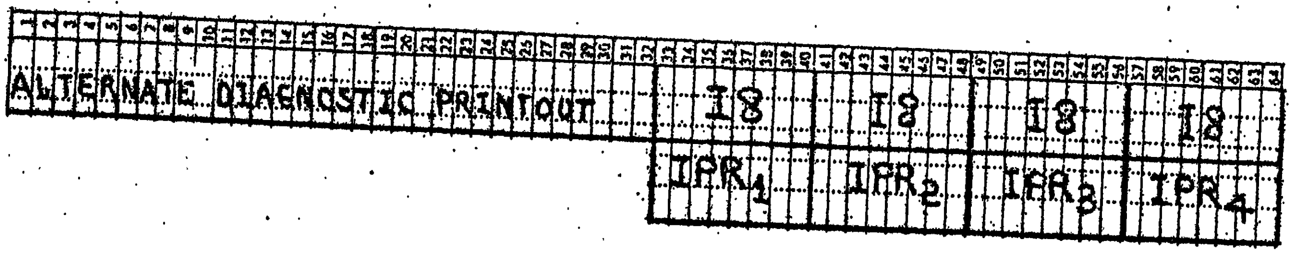
Case 2: If the user wants to start with diagnostic (Step zero), then IPRSOV(16) through IRPSOV(19) should not all be zero. In this case, no "ALTERNATE DIAGNOSTIC PRINTOUT" request is needed, since zero values are the default.

1.0g8 Request for Alternative Diagnostic Printout of the Time-Step Loop

If minus signs are applied to MULT(K) as part of the printout-frequency changes of Section 1.1b, then diagnostic printout codes of the time-step loop are switched. Those of the DIAGNOSTIC request (Section 1.0g7) are in effect initially. Then, at the step of the first change, an alternate set of printout control parameters (IPR(K), K=1, 4) is used instead. These four new variables replace IPRSOV(16) through IPRSOV(19), to control diagnostic printout of the four pieces of the time-step loop. Upon the second such change (second negative MULT), there is a switch back to the original DIAGNOSTIC printout control codes. Etc. (for each minus sign, the two sets of control variables are switched).

The alternate set of printout control parameters (IPR(K), K=1, 4) is initialized to zero at the beginning of execution. Hence if this is what the user wants, he need do nothing special. This corresponds to Case 2 at the end of Section 1.0g7 (begin with diagnostic printout at time zero).

But if the time-step loop is to begin without any diagnostic printout (Case 1, Section 1.0g7), then nonzero IPR(K) must be defined by the user. This is done using a special-request word "ALTERNATE DIAGNOSTIC PRINTOUT", as shown in the following format:



1.0h Miscellaneous Data Parameter Cards

The first non-comment card which fails to be recognized as any of the preceding special request types will be taken to be the beginning of "regular data" for a conventional EMTP data case. This regular data begins with two miscellaneous data cards ---- first one card for floating-point parameters, and then one for integers, as follows:

First misc. data card (floating-point misc. data)

DELTAT	TMAX	XOPT	COPT	EPSILN	TOLMAT	TSTART
E8.0	E8.0	E8.0	E8.0	E8.0	E8.0	E8.0

where

DELTAT ------ (1-8) The time-step size Δt of the numerical integration, in sec. The solution will be calculated at time instants with this spacing: $t=0, \Delta t, 2\Delta t$, etc. seconds.

TMAX ------ (9-16) The termination time T_{max} of the study, in seconds. The simulation thus covers time interval $0 \leq t \leq T_{max}$

XOPT ------ (17-24) Parameter indicating whether inductance or inductive-reactance is to be inputted on all linear branch cards:

- 0 $\Longrightarrow$ All inductance values on branch cards are interpreted as L in mH (millihenries).
- f $\Longrightarrow$ All inductance values on branch cards are interpreted as $\omega L = 2\pi f L$ in Ω (ohms) at frequency f = XOPT .

COPT ------ (25-32) Parameter indicating whether capacitance or capacitive reactance is to be inputted on all linear branch cards:

- 0 $\Longrightarrow$ All capacitance values on branch cards are interpreted as C in μF (microfarads).
- f $\Longrightarrow$ All capacitance values on branch cards are interpreted as $\omega C = 2\pi f C$ in $\mu\mho$ (micromhos) at frequency f = COPT .

EPSILN ------ (33-40) Near-zero tolerance ϵ, used for checking singularity of the real coefficient matrix [G] within the time-step loop, where

$$[G]\vec{v}_{node}(t) = \vec{i}_{node}(t).$$

A blank or zero field is given a default value which is dependent upon the translation being used. With 36-bit floating-point words (single-precision Univac and Honeywell/GE), a default value of 1.E-5 is common; the 60-bit CDC and 64-bit IBM (REAL*8) versions are commonly given default values of 1.E-8

TOLMAT ------ (41-48) A second near-zero tolerance, used for checking singularity of the steady-state phasor (complex) admittance matrix [Y]. A blank or zero field is given default value equal to whatever 'EPSILN' happens to be.

TSTART (49-56) ----- The beginning simulation time. This will normally be zero (the data field can be left blank). If a previously-solved data case is to be restarted, however, then this field must be punched with the terminal (ending) time of that preceding partial simulation.

Second misc. data card (integer misc. data card)

IOUT	IPLOT	IDOUBL	KSSOUT	MAXOUT	IPUN	MEMSAV	ICAT	NENERG	IPRSUP
I8	I8	I8	I8	I8	I8	I8	I8	I8	I8

IOUT (1-8) ----- Parameter providing control over the frequency of the printed transients simulation:

0, 1 ⟹ Output quantities are printed for every time step.

K ⟹ For K >1 , results are printed for every K-th step only; that is, for times t = 0 , $(K\Delta t)$, $(2K\Delta t)$, $(3K\Delta t)$, ... etc.

IPLOT (9-16) ----- Parameter providing control over the frequency of the plotted transients simulation:

0, 1 ⟹ Every computed point will be used for plotting.

M ⟹ For M >1 , only every M-th computed point will be used for plotting. This saves plotting time and reduces storage requirements if, for some reason, a smaller step-size is needed for solution than for graphical output. If the user should punch an even value for M , the program will automatically increment it by one, to make it odd. This is because even values will produce deceptive results for an oscillating curve, graphing only the upper or lower envelope.

-1 ⟹ No plotting is possible, as no permanent file of plot values is created. Use this option if no plots are desired, in order to speed execution.

IDOUBL (17-24) ----- Parameter controlling the printing of a network connectivity table, showing how branches and switches topologically interconnect the network busses.

0 ⟹ No such output is provided.

1 ⟹ A printout of network connectivity is provided. For each node, a list is given of the nodes to which it is connected through physical branches and switches. Mutual coupling between phases of multiphase elements is ignored in this output, as is the capacitance to ground of Pi-circuits and distributed-parameter lines. Since the node name "   " (6 blank characters) which normally signifies ground would not show up in print, the word "TERRA " or "TERRA FIRMA" is used in the connection list.

KSSOUT ---- (25-32) Parameter controlling the printout of all linear-branch line flows, and all voltage-source injections, for the steady-state phasor network solution. See detailed illustration below.

0 ⟹ No such printout

1 ⟹ Yes, print complete steady-state solution.

MAXOUT ---- (33-40) Parameter controlling the printout of maximum absolute values of all output variables, the maximums which occurred during the simulation:

0 ⟹ No such output

1 ⟹ Print the maximums, as calculated using every time step.

2 ⟹ Print the maximums, as calculated using only the time steps t_i for which the output solution vector must be formed for printing or plotting. If the user's branch cards carry a power or energy-output request, every time-step is automatically used, though.

IPUN ---- (41-48) Parameter controlling the punching of terminal conditions of the simulation (at time t = TMAX):

0 ⟹ No such punching.

1 ⟹ Node voltages and branch currents (plus capacitor voltage on series R-L-C branches) at the last time step are punched on cards; these can be used as initial conditions for other studies starting from this state of the system. The present version of the program interrupts punching if a branch with distributed parameters is encountered; in this case, a message "PUNCHING OF CURRENTS STOPPED BECAUSE INFORMATION INSUFFICIENT IN THE PRESENCE OF DISTRIBUTED PARAMETERS" is printed. The transient state of a branch with distributed parameters would have to be defined by the entire voltage and current profile along the line; this causes complications in the input/output phases, which have not yet been incorporated.

-1 ⟹ An extra, special card will immediately follow this second misc. data card, to vary the printout frequency as described in Section 1.1 . See also Section 1.0e10 .

MEMSAV ---- (49-56) Parameter controlling the dumping of memory onto disk at the end of the simulation (time TMAX), for subsequent use with the "START AGAIN" request of Section 1.0e15 :

0 ⇒ No such memory saving will occur.

1 ⇒ Yes, save the memory contents for later use.

WARNING! The dumping of memory onto disk in this way is an installation-dependent feature which has not been implemented on all computer systems. Modules KATALG and PFATCH are involved (see Section 0.5). Consult the installation-dependent information for your computer system at the beginning of this manual, if in doubt.

RESTRICTION : The "START AGAIN" reactivation of a previously-halted simulation can only be guaranteed if the same EMTP version is used. An internal check is made on the size of /BLANK/ and /LABEL/ , with an EMTP error stop resulting if these figures do not match for the two program versions. The dimensioning must be identical, then.

ICAT ---- (57-64) Parameter which controls the permanent disk storage of plot data points which are accumulated on logical unit number 4 during the simulation:

0 ⇒ No permanent storage will be provided, though conventional batch-mode plotting at the conclusion of the solution process is possible. But once the computer job ends, the plot file will be lost.

1 ⇒ Permanent storage of the plot data file will be provided at the conclusion of the solution process; these will be cataloged on the disk using the date and the time (MM/DD/YY HH.MM.SS) when the data case began execution (see initial line-printer output of a data-case solution). No conventional batch-mode plotting of the results in this case will be allowed (the T.P. will skip over plot cards, discarding them until it finds the blank card which terminates plot cards).

2 ⇒ Combination of the above. That is, the plot data file is saved on disk for later re-use, plus, conventional batch-mode plotting requests are honored.

WARNING! The saving of plot data points on disk is an installation-dependent feature which has not been implemented on all computer systems. Modules KATALG and PFATCH are involved (see Section 0.5). Consult the installation-dependent information for your computer system at the beginning of this manual, if in doubt. The practical production use of such files is for CRT plotting (see description of Section 5.).

NENERG —— (65-72) Control parameter related to the running of multiple-energization studies (either "STATISTICS" or "SYSTEMATIC").

0 ⇒ Conventional, single, deterministic T.P. simulation is desired; no dice rolling!

K ⇒ For $K > 0$, this is a request for a statistical study of this data case, in which K energizations (switch closings) will be performed.

For $K < 0$, this is a request for a systematic study of this data case, in which $|K|$ energizations will be performed.

See the section on switch cards for a complete discussion of such studies (both "STATISTICS" and "SYSTEMATIC"). Should "NENERG" be punched nonzero, an added special statistics or systematic miscellaneous data card must follow, giving necessary scalar parameters for the study.

IPRSUP —— (73-80) Parameter controlling the output of program diagnostic printout. Production runs should always leave this field blank (or punch a zero). Beware of astronomical paper requirements in using this capability; use only with understanding, or upon the advice of program maintenance.

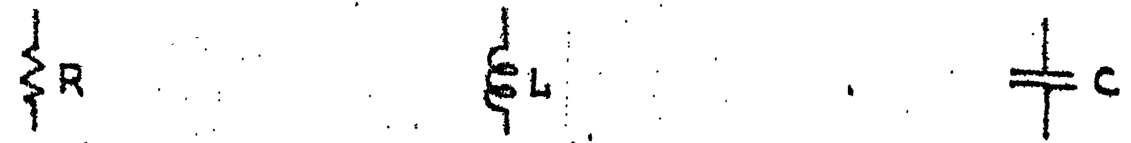
0 ⇒ there will be no diagnostic printout, unless such was selectively requested using the "DIAGNOSTIC" key-word card of Section 1.0g7 .

M ⇒ For increasingly-positive "M" , more and more diagnostic printout will be generated. Such a positive "M" over-rides any selectively-requested diagnostic printout (key-word "DIAGNOSTIC").

Sinusoidal steady-state solution output

In order to determine initial conditions for starting the transients solution, a single-frequency, sinusoidal, steady-state solution is automatically calculated by the Transients Program. This produces a phasor solution to the linear network which the user inputted ---- linear because all nonlinear elements are either disconnected during the solution, or are assumed to operate in their normal linear range.

Excitation for these solutions consists of only sinusoidal sources (Type 14 sources of Section 1.6) for which TSTART < 0 has been punched. Solution is only for a single frequency f_{STEADY}, that frequency read from the first Type 14 source card. All Type 14 sources within ±1% of this frequency are used; all others are ignored during the steady-state solution.



$$v = Ri \Downarrow \bar{V} = R\bar{I} \qquad v = L\frac{di}{dt} \Downarrow \bar{V} = j\omega L\bar{I} \qquad i = C\frac{dv}{dt} \Downarrow \bar{I} = j\omega C\bar{V}$$

If the user is interested in printout of the above steady-state solution, he has two options:

a) Complete Solution. By punching a "1" in column 32 of the Integer Misc. Data Card (Section 1.0h; the 2nd miscellaneous data card), complete printout of the flows in all network branches is produced. The printout includes complex currents and powers, as well as terminal voltages for the two ends of each branch, in both rectangular and polar form.

b) Transients variables only. By setting T_{max} of the Floating-Point Misc. Data Card to be non-positive (see Section 1.0h; columns 9-16 of the first miscellaneous data card), the EMTP will never reach the transients mode in solving the data case. Rather, the steady-state solution is found, and then a special phasor printout of only those variables normally printed during the transient run (see Section 1.8) occurs. The case is then terminated following this printout.

Note that following the output of option a), a transient solution to the network is allowed. Also, either, both, or neither steady-state printout can be requested, since they are independent. See Section 2.2 for sample output of this type.

Should one or more switch currents be desired, a branch of small resistance or inductance can be inserted in series with a switch; then the column-80 punch (see Section 1.21) allows the outputting of the current in question.

The formula used for the power flow calculation is $P + jQ = V \cdot I^* / 2$. Hence it is implicitely assumed that sources are specified in peak, and not in rms, terms. Such a use of peak quantities will be found to be consistent with source-input rules of Section 1.6 . For example, a nominal Wye-connected voltage source for 500kV would have amplitude $500\sqrt{2/3} = 408248$ volts. With sources given in volts and amps, power then comes out in watts or vars.

The complete steady-state solution output provides printout on the extreme right of the page for power loss, branch by branch (see example of Section 2.2). Assuming that the branch in question connects nodes k and m as shown, then by definition, the program prints out the following:

$$P_{loss} + j\,Q_{loss} = (P_{km} + P_{mk}) + j\,(Q_{km} + Q_{mk})$$

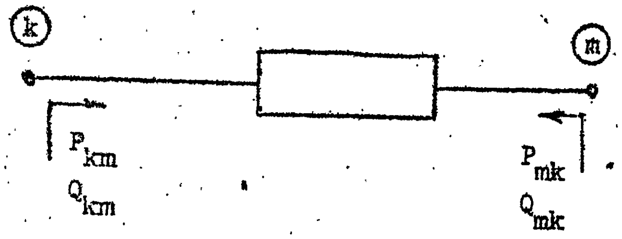


Fig. 1. Branch (k,m)

For simple series R-L-C branches, this is indeed the true loss figure for the branch ---- the heating loss (considering real power only) in resistance of the branch.

But for distributed-conductor or Pi-equivalent branches, the loss figure so printed is not really loss at all; it is simply the sum of the power inputs at the two ends.

BEWARE!

Conservation of energy dictates that power in equals power out. But only if terminals k and m were the only connection to branch (k,m) would the printout actually give true branch loss. But mutual coupling (capacitive and/or inductive) between branch (k,m) and other branches provides additional paths for power entry and/or exit (see Fig. 2). Thus adding the k-to-m and the m-to-k powers does not provide loss.

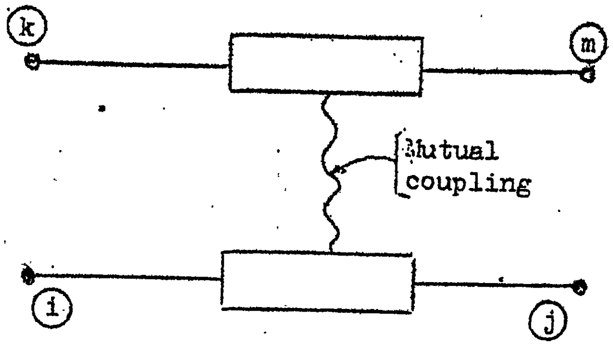


Fig. 2. Mutual coupling with branch (k,m) may be present.

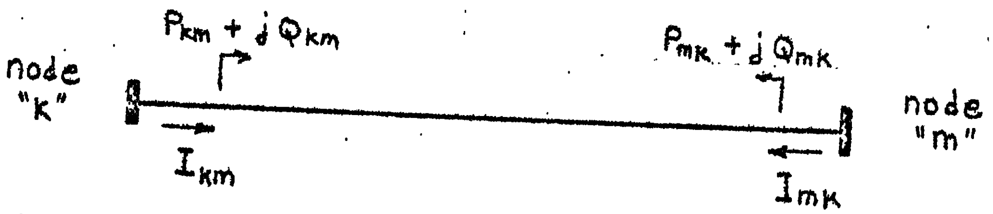
CONCLUSION: With distributed or Pi-equivalent branches, do not interpret the printed loss figure (P or Q) of the complete steady-state solution printout as loss attributable uniquely to the branch in question. The one exception to this warning is in the single-phase (uncoupled) case, where there is no problem.

A sample of the complete steady-state solution printout is shown below. This begins with branch flows, as follows:

```
SINUSOIDAL STEADY STATE SOLUTION, BRANCH BY BRANCH.  ALL FLOWS ARE AWAY FROM BUS, AND REAL PART, MAGNITUDE, OR P
IS PRINTED ABOVE THE IMAGINARY PART, THE ANGLE, OR Q.   SOLUTION FREQUENCY =   .60000000E+02   HERTZ.
 BUS K                               NODE VOLTAGE                        BRANCH CURRENT
            BUS M      RECTANGULAR           POLAR         RECTANGULAR           POLAR           POWER FLOW       POWER LOSS
                                                                                                   P AND Q          P AND Q
 B3A
                       .4043549E+06     .4082102E+06      .3484110E+03     .3562553E+03
                       .5599947E+05           7.8849      .7434821E+02          12.0458      .7252187E+08     .5669779E+06
            B4A                                                                             -.5275966E+07    -.1025542E+09
                       .3779949E+06     .3782561E+06     -.3993057E+03     .6397687E+03
                       .1405543E+05           2.1295      .4998589E+03         128.6191     -.7195489E+08
                                                                                            -.9727826E+08
 B3B
                      -.1538785E+06     .4082102E+06     -.1098161E+03     .3562553E+03
                      -.3781779E+06        -112.1151     -.3389064E+03        -107.9542      .7252187E+08     .5669779E+06
            B4B                                                                             -.5275966E+07    -.1025542E+09
                      -.1768251E+06     .3782561E+06      .6325434E+03     .6397687E+03
                      -.3343809E+06        -117.8709      .9587942E+02           8.6191     -.7195489E+08
                                                                                            -.9727826E+08
 B3C
                      -.2906724E+06     .4082102E+06     -.2385929E+03     .3562553E+03      .7252187E+08     .5669779E+06
```

: Etc.

Note that the first branch connects node "B3A" with node "B4A". Using "k" and "m" as abbreviated subscripts for these, the following diagram shows which quantities are printed out for this branch:



In mathematical notation, the following answers will be read from the printout:

$$V_k = 404350.9 + j55999.47 = 408210.2 \underline{/\ 7.8849^\circ}$$
$$V_m = 377994.9 + j14055.43 = 378256.1 \underline{/\ 2.1295^\circ}$$
$$I_{km} = 348.4110 + j74.34821 = 356.2553 \underline{/\ 12.0458^\circ}$$
$$I_{mk} = -399.3057 + j499.8589 = 639.7687 \underline{/\ 128.6191^\circ}$$
$$P_{km} + jQ_{km} = (\ 72.52187 - j5.275966\ )\cdot 10^6$$
$$P_{mk} + jQ_{mk} = (-71.95489 - j97.27826\ )\cdot 10^6$$
$$P_{loss} + jQ_{loss} = \text{sum of above} = (\ .5669779 - j102.5542\ )\cdot 10^6$$

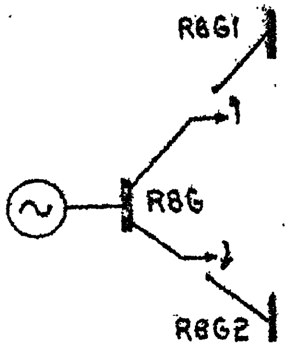
After the last such branch-flow printout, there will be an injection printout for all non-ground nodes which are connected to voltage sources during the steady-state phasor solution. The general format is similar to that which has just been illustrated for branches:

```
TION AT NODES WITH KNOWN VOLTAGE.     NODES SHORTED TOGETHER BY SWITCHES ARE SHOWN AS A GROUP OF NAMES, WITH
PRINTED RESULT APPLYING TO THE COMPOSITE GROUP.   THE ENTRY *MVA* IS  SQRT(P**2 + Q**2)  IN UNITS OF POWER.
E *P.F.*  IS THE ASSOCIATED POWER FACTOR.
          NODE               SOURCE NODE VOLTAGE            INJECTED SOURCE CURRENT             INJECTED SOURCE POWER
          NAME          RECTANGULAR         POLAR         RECTANGULAR          POLAR            P AND Q     MVA AND P.F.
          GENA
                       .1966918E+05     .2122890E+05      .1605429E+05     .2396948E+05
                      -.7986827E+04         -22.1000     -.1779876E+05         -47.9499     .2289652E+09   .2544229E+09
          GENB                                                                              .1109321E+09   .8999395E+00
                      -.1675139E+05     .2122890E+05     -.2344132E+05     .2396948E+05
                      -.1304068E+05        -142.1000     -.5004043E+04        -167.9499     .2289652E+09   .2544229E+09
          GENC                                                                              .1109321E+09   .8999395E+00
                      -.2917797E+04     .2122890E+05      .7387033E+04     .2396948E+05     .2289652E+09   .2544229E+09
```

: Etc.

Assuming that we are considering node "k" , then the next to the last column gives the injection $P_k + jQ_k$ ------ positive if from the source into the network. The final column shows the magnitude of this complex number, plus the power factor (the cosine of the angle which has tangent Q_k / P_k).

One special feature of the injection printout concerns the effect of closed switches. There will only be one double line of injection printout for each point of known, equal voltage in the network. For example, suppose that three nodes happen to be shorted together by closed switches during the steady-state phasor solution, as per the sketch at the right. Then there would only be one line of injection printout for these three EMTP nodes. All three node names in question would be listed contiguously in the "NODE NAME" column, however, as indication of the node combination or shorting which has occurred:



RBG1
RBG2
RBG

The user should be warned that the aforementioned steady-state phasor branch-flow printout shows an entry for each component in the EMTP branch table (List #2 of Section 0.6), in order. Since the branch table is not sorted (as of 1977), the printout is in the order of data input to the branch table. Nonetheless, there can be confusion in some cases, due to internally-defined nodes and branches. The following comments document the way data can thus be disguised:

1) Switched-inductance and switched-resistance elements each contribute two uncoupled branches to the EMTP branch table. The "saturation branch" will always have "......" as the name of one end (variable "TRASH" as defined in module "SYSDEP" of Section 0.5), and it will carry zero current (since the switch is open in the steady state). This is only a very minor inconvenience today, now that such elements are used very little (see Sections 1.41 and 1.42).

2) The saturable "TRANSFORMER" of Section 1.25 may contribute a number of entries to the EMTP branch table. See the list of these elements under Message 48 of Section 2.2b . At least in this case all nodes are distinct, and user-defined (so that there is no ambiguity).

3) For the Type-16 EMTP source component of Section 1.61 , the EMTP internally defines two branches (both resistors) and two nodes ("TYP-16" and "......"). There will be two entries in the steady-state branch-flow printout for each Type-16 component, then.

4) Each Type-98 pseudo-nonlinear inductor (Section 1.29) is represented by a linear inductor, for purposes of steady-state solution. The same holds true for each Type-93 (tru) nonlinear inductor of Section 1.33 .

5) Flashover branches are all open circuits during the steady-state phasor solution. They are not in the branch table (List #2) at all, and have no associated steady-state printout. Included in this category are:

   a) Type-91 time-varying resistance of Section 1.31 ;
   b) Type-92 (true) nonlinear resistance of Section 1.32 ;
   c) Type-94 dynamic surge arrester of Section 1.34 .

There also is steady-state (initial condition) printout for dynamic synchronous machine (S.M.) source components (Section 1.62), although the requests for such printout are handled separately as part of the S.M. data. See "Class 5 S.M. Data" of Section 1.62 , variables "JPAR" and "JMIC" of columns 1-2 . Note that such printout is separately controlled for each machine, at present. Anyway, should such printout be requested for one or more machines, the aforementioned injection printout will be followed by the initial condition printout for each machine, of which the following is an illustrative example:

```
1A
'ACA'          DATA PARAMETERS AND INITIAL CONDITIONS OF NEXT MACHINE FOLLOW.  --------------------------------------------
                                                                                                                  DUAL,   1ST HALF
CHINE INDUCTANCE AND RESISTANCE PARAMETERS IN PER UNIT
  .1859544E+01      LF   = D-AXIS FIELD SELF INDUCTANCE
  .1730000E+01      LAF  = D-AXIS FIELD-ARMATURE MUTUAL INDUCTANCE
  .1730000E+01      LFKD = D-AXIS FIELD-DAMPER MUTUAL INDUCTANCE
  .1920000E+01      LD   = D-AXIS ARMATURE SELF INDUCTANCE (SYNCHRONOUS REACTANCE)
  .1730000E+01      LAKD = D-AXIS ARMATURE-DAMPER MUTUAL INDUCTANCE
  .1839007E+01      LKD  = D-AXIS DAMPER SELF INDUCTANCE
  .2254482E+01      LG   = Q-AXIS CIRCUIT 1 SELF INDUCTANCE
  .1650000E+01      LAG  = Q-AXIS CIRCUIT 1-ARMATURE MUTUAL INDUCTANCE
  .1680000E+01      LG12 = Q-AXIS CIRCUIT 1-CIRCUIT 2 MUTUAL INDUCTANCE
  .1854000E+01      LQ   = Q-AXIS ARMATURE SELF INDUCTANCE
  .1669000E+01      LAKQ = Q-AXIS CIRCUIT 2-ARMATURE MUTUAL INDUCTANCE
  .1744412E+01      LKQ  = Q-AXIS CIRCUIT 2-SELF INDUCTANCE
  .1220000E+02      L0   = ZERO SEQUENCE REACTANCE
  .1000000E-05      RN   = RESISTIVE PART OF NEUTRAL GROUNDING IMPEDANCE
  .1000000E-05      LN   = INDUCTIVE PART OF NEUTRAL GROUNDING IMPEDANCE
  .1582725E-02      RF   = RESISTANCE OF FIELD WINDING
  .1725944E-02      RA   = ARMATURE RESISTANCE
  .1515400E-01      RKD  = D-AXIS DAMPER RESISTANCE
  .7772177E-02      RG   = Q-AXIS CIRCUIT-1 RESISTANCE
  .2045931E-01      RKQ  = Q-AXIS CIRCUIT-2 RESISTANCE
ANICAL PARAMETERS OF MACHINE, IN PER UNIT.
MENT OF INERTIA        SELF-DAMPING COEFFICIENTS OF MASS
 OF ROTOR MASS       SPEED-DEVIATION        ABSOLUTE-SPEED            MUTUAL-DAMPING COEFF.      TORSIONAL SPRING CONSTANT
  .1393335E+04         .1334011E-07               .0                 (WITH FOLLOWING MASS)        (WITH FOLLOWING MASS)
                                                                              .0                           .0
 CURRENT INJECTED INTO NETWORK AT GENERATOR BUS, IN PHASE COORDINATES.   FOR A DUAL-MACHINE BUS,
 IS THE TOTAL INJECTION ( "A" + "B" ).   THE FIRST LINE DISPLAYS THE CURRENTS AS FOUND BY THE PHASOR NETWORK
ITION (WHICH MAY BE UNBALANCED, IF THE NETWORK IS).   THE 2ND LINE SHOWS ONLY THE POSITIVE-SEQUENCE COMPONENT.
 IS USED FOR MACHINE INITIALIZATION.   MAGNITUDES OF THE CURRENTS ARE IN UNITS OF  PER UNIT.
              ARMATURE OF PHASE "A"                         ARMATURE OF PHASE "B"
             MAGNITUDE       DEGREES                      MAGNITUDE        DEGREES                ARMATURE OF PHASE "C"
AL        .5235359E+00   103.8553000                                                              MAGNITUDE       DEGREES
SEQ.      .8316294E+00    21.1893932                    .1386364E+01   -102.2184307              .1131931E+01   118.4374150
                                                        .8316294E+00    -98.8106068              .8316294E+00   141.1893932
TURE CURRENTS OF GENERATOR IN ROTATING REFERENCE FRAME (D-Q-0 COORDINATES), IN PER UNIT.
          ID              IQ                I0
   .1937393E+00.    .4703755E+00    .0
URE CURRENTS OF GENERATOR IN PHASE (REAL COIL) COORDINATES, IN PER UNIT.
IVE-SEQUENCE COMPONENT ONLY, AS USED FOR INITIALIZATION OF THE MACHINE.
          ARMATURE OF PHASE "A"                          ARMATURE OF PHASE "B"
         MAGNITUDE        DEGREES                       MAGNITUDE        DEGREES                 ARMATURE OF PHASE "C"
     .1333722E+05     21.1893932                      .1333722E+05    -98.8106068                 MAGNITUDE       DEGREES
                                                                                                .1333722E+05   141.1893932
 CURRENT OF GENERATOR, IN PER UNIT.
  .1172413E+01
ROMECHANICAL TORQUE OF GENERATOR, IN PER UNIT.
  .3162321E+00
NICAL ANGLES OF ROTOR MASSES, IN UNITS OF  (DEGREES)  OR  (RADIANS) .
          -.8107134    "THETA"  FOR MASS NO.  1   (IN RADIANS)
R VELOCITIES OF ROTOR MASSES, IN PER UNIT.
         1.0000000    "OMEGA"  FOR MASS NO.  1

B
A'          DATA PARAMETERS AND INITIAL CONDITIONS OF NEXT MACHINE FOLLOW.  --------------------------------------------
                                                                                                                  DUAL,   2ND HALF
E INDUCTANCE AND RESISTANCE PARAMETERS IN PER UNIT
1859944E+01      LF   = D-AXIS FIELD SELF INDUCTANCE
1730000E+01      LAF  = D-AXIS FIELD-ARMATURE MUTUAL INDUCTANCE
1730000E+01      LFKD = D-AXIS FIELD-DAMPER MUTUAL INDUCTANCE
1920000E+01      LD   = D-AXIS ARMATURE SELF INDUCTANCE (SYNCHRONOUS REACTANCE)
1730000E+01      LAKD = D-AXIS ARMATURE-DAMPER MUTUAL INDUCTANCE
1839007E+01      LKD  = D-AXIS DAMPER SELF INDUCTANCE
```

User-supplied name for phase "a" of armature connection

Note that this is a "dual" machine bus (2 in parallel)

Machine Parameters

Note extreme imbalance. One phase of connecting line was open circuited

Note single row of ~~table~~ table, since only one mass. No inter-mass torques!

Printout for the 2nd half of dual machine follows the 1st

[illegible] EXTENSIONS TO MISC. DATA CARDS

There are two fields on the integer miscellaneous data card which may require the input of additional data, data which is to immediately follow the integer (2nd) miscellaneous data card, in the following order:

a) If 'NENERG' of columns 65-72 is nonzero, a special miscellaneous data card must immediately follow the integer miscellaneous data card, for this "STATISTICS" or "SYSTEMATIC" case.

b) If 'IPUN' of columns 41-48 has value -1, the preceding card (if any) is to be followed by a card which varies the printout frequency.

The format and meaning of these additional cards is as described in the [illegible] which follow:

[illegible] "STATISTICS" or "SYSTEMATIC" Miscellaneous Data Card (Optional)

If and only if parameter 'NENERG' of the integer miscellaneous data card has a positive value, the following additional special "STATISTICS" miscellaneous data card is required:

ISW	ITEST	IDIST	AINCR	XMAXMX	DEGMIN	DEGMAX	STATFR	SIGMAX	NSEED
I8	I8	I8	F8.0	F8.0	F8.0	F8.0	F8.0	F8.0	I8

WHERE:

ISW
- 1 ⇒ Request for the printed output of all switch closing times, for every energization.
- 0 ⇒ No printed output of switch closing times will occur.

ITEST
- 0 ⇒ An extra, randomly-selected offset time, calculated using the parameters "DEGMIN", "DEGMAX", and "STATFR", is to be added to the randomly-generated switch closing times, for each energization.
- 1 ⇒ No such additional offset is added.

IDIST
- 0 ⇒ All randomly-generated switch closing times (for "STATISTICS" switches) will have Gaussian (normal) distribution.
- 1 ⇒ All randomly-generated switch closing times will have a uniform distribution.

AINCR ~ The post-solution statistical tabulation of overvoltages, following the solution of all "NENERG" energizations, will use a voltage discretization increment of "AINCR" in per unit. A zero or blank field will be given default value AINCR = 0.05 per unit.

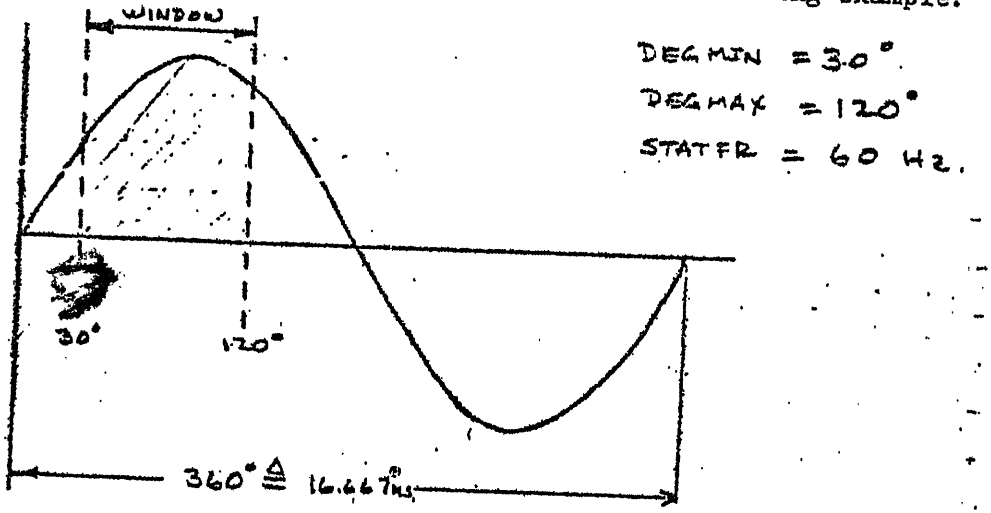
Note : Variable "AINCR" is also used as a flag for the request of additional printout by the EMTP. Add a bias of "55." in order to also produce the familiar base-case printout of minima and maxima (along with their associated times of occurance) for each energization. This printout is in addition to, and not a replacement for, the regular printout that occurs for each energization.

XMAXMX ~ The maximum per unit overvoltage that the counting algorithm will consider. This is a per unit bound on the tabulated overvoltage distributions which will be outputed, with a default value of 2.0 assumed if the user should input a zero or blank value.

DEGMIN
DEGMAX
STATFR ~ Parameters which are used (and have meaning) if and only if statistics parameter "ITEST" of columns 9-16 of the same card is zero or blank. In this case, the additional random time which is to be added to the randomly-generated switch closing times is produced from these three parameters for each energization using the following formula:

$$T_{offset} = \left\{ \frac{1/STATFR}{360} \right\} \cdot \left\{ (1-\alpha)\, DEGMIN + \alpha \cdot DEGMAX \right\}$$

where α is a random number which is uniformly distributed over the unit interval (0.0, 1.0) . "DEGMIN" and "DEGMAX" are thus minimum and maximum angles in degrees which define a "window" of a sine wave having frequency "STATFR" Hz., from which the added time is randomly selected according to a uniform distribution. As an illustrative sample sketch, consider the following example:



Blank or zero values for fields "DEGMIN" and "DEGMAX" are given default values of zero and 360 degrees, respectively; the corresponding default value for a blank or zero "STATFR" will depend on the particular translation being used, with a value of 60 generally used in North America (where virtually all electric power is of frequency 60 Hz). Default values are set within installation-dependent module "SYSDEP" of overlay number 1.

SIGMAX — For a Gaussian (normal) distribution, "SIGMAX" gives the point at which the "tails" of the distribution will be truncated, for calculating the random switch times. This is as a multiple of the standard deviation, and is symmetric about the mean. A zero or blank field will be given a default value of 4.0, which means that no random switch times further removed than 4σ from the mean will be allowed.

NSEED — Parameter which controls whether or not the random switch times will be identical, should a given "STATISTICS" data case be re-run a second time:

- 1 ⇒ a re-run of the data case will produce identically the same answers; the random-number generating algorithm uses a seed which does not depend on the time of day.
- 0 ⇒ a re-run of the data case will produce different answers; the seed does depend on the time of day.

②

If and only if parameter "NENERG" of the integer miscellaneous data card has a negative value, the following additional special "SYSTEMATIC" miscellaneous data card is required:

ISW	ITEST		AINCR	XMAXMX
I8	I8		F8.0	F8.0

ISW — Same meaning as for "STATISTICS" immediately above.

ITEST

- 0 ⇒ The inputted switch-time TCLOSE, which is read from a "SYSTEMATIC" switch card, is understood to be the mean switch time. The variation will be around such center values, then.
- 1 ⇒ The inputted switch-time TCLOSE, which is read from a "SYSTEMATIC" switch card, is understood to be the minimum or beginning switch time. The variation will be for times greater than this, then.

AINCR — Same meaning as for "STATISTICS" immediately above.

XMAXMX — Same meaning as for "STATISTICS" immediately above.

③

If and only if parameter "NENERG" of the integer miscellaneous data card has a positive value, and field "ISW" of the "STATISTICS" miscellaneous data card is punched with the integer 4444 , then a special test of the random switch times is produced. In this case, no simulations are actually produced. Rather, the random switch closing times are just generated, and subsequently tabulated statistically, so as to compare the observed distribution with the expected theoretical distribution. For this case where "ISW" is punched with value 4444 , two other fields of the "STATISTICS" miscellaneous data card also take on special meaning:

ISW				AINCR					SIGMAX
I8				F8.0					F8.0

ISW —— Punched with special flag 4444 , in this case.

AINCR —— The sample and theoretical cumulative distribution functions will be tabulated at a number of uniformly-spaced time instants. The time-spacing of this tabulation is "AINCR" , as a multiple of the standard deviation σ of the switch in question.

SIGMAX —— The range of the just-described tabulated comparison is "SIGMAX" on either side of the mean closing time, as a multiple of the standard deviation σ .

A number of comments might be appropriate, as to usage of this diagnostic feature :

Comment 1 : Characteristic printout of this feature is a series of tabulations for different pairs of switches. Recall that if closing times for switch "A" and switch "B" are both of Gaussian (normal) distribution, then the difference will also be Gaussian and will have mean and standard deviation given by:

$$\bar{T} = \bar{T}_A - \bar{T}_B \qquad \sigma = \sqrt{\sigma_A^2 + \sigma_B^2}$$

It is this difference of closing times which is checked, and this is not the same as just looking at the closing times of any one switch. Recall that no random number generating algorithm is truly random; the K+1st number is a function of the K-th number, somehow (usually). Since there is only a finite number of different bit permutations within a computer word, every generating algorithm must eventually repeat. Presumably the period is so large that it is of no practical interest for EMTP usage. But what about correlation of successive numbers? I am still haunted by Stanford's assessment of IBM's random number generator, as reported in the July, 1975 issue of DATAMATION (in the Software and Services section):

> "IBM's Scientific Subroutine Package, a collection of over 250 routines, is not getting high marks at Stanford Univ., and will be expelled before the end of the summer. ..... But the real reason SSP is being bounced, says the school, is that many of its routines are inaccurate, obsolete and downright dangerous to use. For example, in RANDU, a uniform random number generator, consecutive triples of numbers are completely correlated. .... "

Well, for M Gaussian switches, there will be M (M-1) / 2 such pairings of switches. For each, there will be one tabulated output, of which the following (extracted from a modified version of UTPF Test Case # 77) are typical:

```
SWITCH PAIR   2               'CSW1  ' TO  'C1    '  AND  'ASW1  ' TO  'A1    '
TIME         -3.5000 -3.0000 -2.5000 -2.0000 -1.5000 -1.0000 -0.5000  0.0000  0.5000  1.0000  1.5000  2.0000  2.5000  3.0000
SAMPLE        0.0000  0.0000  0.0000  0.0200  0.0700  0.1500  0.3000  0.4900  0.6700  0.8100  0.9100  0.9500  1.0000  1.0000
THEORETICAL   0.0000  0.0013  0.0062  0.0228  0.0668  0.1587  0.3085  0.5000  0.6915  0.8413  0.9332  0.9772  0.9938  0.9987

TIME          3.5000  4.0000
SAMPLE        1.0000  1.0000
THEORETICAL   0.9998  1.0000

SWITCH PAIR   3               'CSW1  ' TO  'C1    '  AND  'BSW1  ' TO  'B1    '
TIME         -3.5000 -3.0000 -2.5000 -2.0000 -1.5000 -1.0000 -0.5000  0.0000  0.5000  1.0000  1.5000  2.0000  2.5000  3.0000
SAMPLE        0.0000  0.0000  0.0000  0.0300  0.0600  0.1800  0.3100  0.4600  0.6200  0.8200  0.9200  0.9400  1.0000  1.0000
THEORETICAL   0.0000  0.0013  0.0062  0.0228  0.0668  0.1587  0.3085  0.5000  0.6915  0.8413  0.9332  0.9772  0.9938  0.9987

TIME          3.5000  4.0000
SAMPLE        1.0000  1.0000
THEORETICAL   0.9998  1.0000
```

Concerning units, it will be noted that everything has been normalized. The printed "TIME" row gives the number of standard deviations from the mean. The corresponding actual time in seconds could be found from

$$t_k = \overline{T} + \sigma * \mathrm{TIME}(K)$$

Entries in the "TIME" row should normally vary from -SIGMAX to +SIGMAX ; I note that one compartment is missing on the left, since tabulations correspond to the right edge of the compartment.

Comment 2 : The just-described tabulation only applies to Gaussian (normal) switch-closing times. If one or more switches happen to be either deterministic (non-STATISTICS) or uniformly-distributed, they are ignored for purposes of this special tabulation.

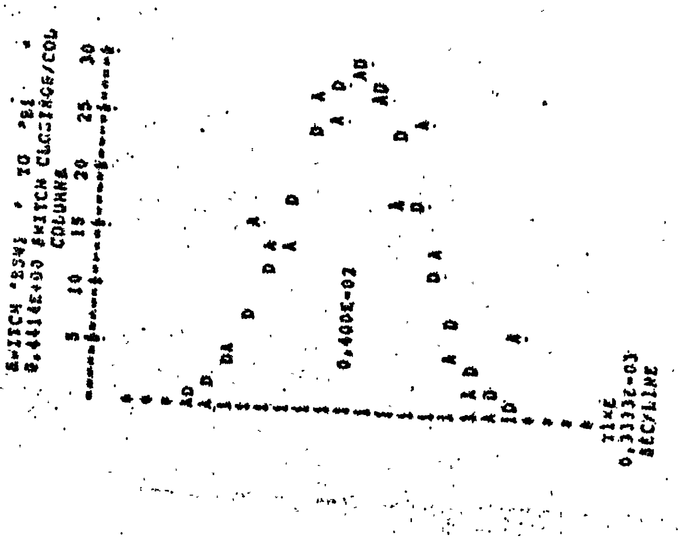
Comment 3 : Recall that miniature printer plots of individual switch closing times are outputted at the end of the printout for a conventional "STATISTICS" solution. See Section 1.8b for an example. Well, such plots of switch closing times will also end the run being considered here. All parameters and assumptions related to this output remain unchanged.

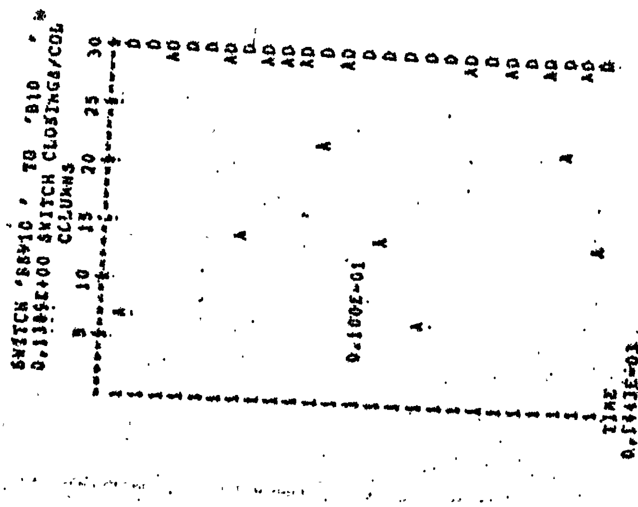
Comment 4 : A complete EMTP data case must be used, at least through the blank card which terminates switch cards (see Section 1. for the structure of EMTP data cases). EMTP source cards and all later cards of a conventional case are optional; if so supplied by the user, they will be skipped by the EMTP as it searches for a "BEGIN NEW DATA CASE" record (just as if an EMTP error stop had occurred)

An example of such record skipping can be seen in the sample output of Section 2.4 . The user should remember to always supply such a separator record, even if no other data case follows, in order to avoid reading an end-of-file mark on the input unit "LUNIT5" .

For those knowing something about the EMTP overlay structure, it is worth summarizing where program control is transferred during such a data case. First, data input is quite normal through the blank card which ends EMTP switch cards, as read in "OVER5" . Then there is a jump to "OVER12" for all switch closing time calculation and the printout of Comment 1 ; then there is a jump to "OVER29" for the output as discussed in Comment 3 . Finally, excess cards are discarded in "OVER54" (looking for the "BEGIN NEW DATA CASE" card), before the loop back to "OVER1" to start a new data case.

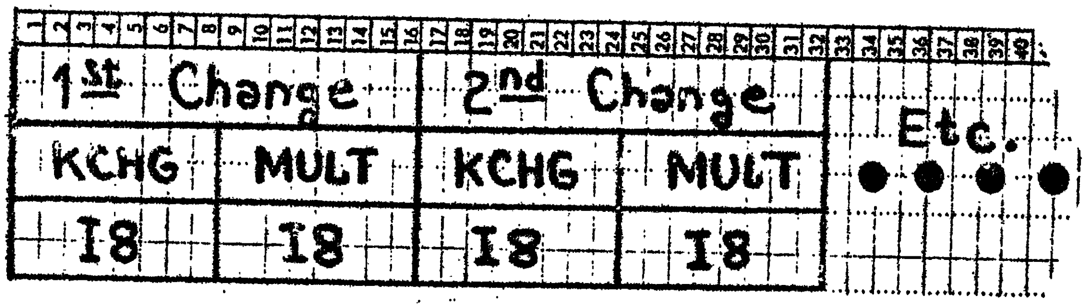
```
ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP), DIGITAL (DEC) VAX-11/780 TRANSLATION AS USED BY BPA IN PORTLAND, OREGON  97208
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS.)= 03/31/80  17.27.13  ANY PLOTS NEAR SAME FIGURES.
IF IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE 554-PAGE EMTP USER'S MANUAL DATED NOVEMBER, 1977.   VERSION = "M27." .
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF   /LABEL/   EQUALS 200123  INTEGER WORDS.   703  1050  2500    30  9300
   125  6100  5000    30   130   100   140     5  9000   400     9     1    30  9990   500    72   200  3000     6  3700
-------------------------------------------------------------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA ! INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER.
                                                  0         1         2         3         4         5         6         7         8
                                                  0         0         0         0         0         0         0         0         0
-------------------------------------------------------------------------------------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.              !BEGIN NEW DATA CASE
MISC. DATA.     0.100E-03   0.200E-01   0.500E+02 ! 100.E-6   20.E-3        50.
MISC. DATA.     10   1  1  1  1  0  0   0100   0  !        10         1         1         1         1
STATISTICS DATA.    4444        1       0   0.3000 !      4444         1                   0.5       3.                        100
SERIES R-L-C.    0.000E+00  0.700E+01  0.000E+00 ! 0GENA   A1                                7.                           4.0
SERIES R-L-C.    0.000E+00  0.700E+01  0.000E+00 ! 0GENB   B1                                7.
SERIES R-L-C.    0.000E+00  0.700E+01  0.000E+00 ! 0GENC   C1                                7.                                       3
SERIES R-L-C.    0.000E+00  0.700E+01  0.000E+00 ! 0GENA   A10                               7.                                       3
SERIES R-L-C.    0.000E+00  0.700E+01  0.000E+00 ! 0GENB   B10                               7.
SERIES R-L-C.    0.000E+00  0.700E+01  0.000E+00 ! 0GENC   C10                               7.
0.330E+00 0.211E+01 0.645E+00 0.933E+02 0.301E-02!-1ASW1   A5                        .3     2.1146 0.645 50.     0
0.265E-01 0.540E+00 0.210E-01 0.261E+03 0.274E-03!-2BSW1   B5                        .0268  .5397  0.021 50.     0
RD OR LATER UNIF.-TRANSPOSED DISTRIBUTED COND.   !-3CSW1   C5
SERIES R-L-C.    0.100E+01  0.000E+00  0.000E+00 ! 0A5     A5F                     1.
SERIES R-L-C.    0.100E+01  0.000E+00  0.000E+00 ! 0B5     B5F                     1.
SERIES R-L-C.    0.100E+01  0.000E+00  0.000E+00 ! 0C5     C5F                     1.
REFERENCE BRANCH.    COPY  'ASW1  ' TO 'A5    '  !-1A5F    ASW10 ASW1  A5
REFERENCE BRANCH.    COPY CONT.                  !-2B5F    BSW10
REFERENCE BRANCH.    COPY CONT.                  !-3C5F    CSW10
ANK CARD TERMINATING BRANCH CARDS.               !
ITCH.     0.20E-02  0.10E-03  0.00E+00  0.00E+00 !  A1     ASW1           2.E-3     .1E-3
ITCH.     0.40E-02  0.10E-02  0.00E+00  0.00E+00 !  B1     BSW1           4.E-3     1.E-3                 STATISTICS
ITCH.     0.60E-02  0.10E-02  0.00E+00  0.00E+00 !  C1     CSW1           6.E-3     1.E-3                 STATISTICS
ITCH.     0.80E-02  0.10E+01  0.00E+00  0.00E+00 !  A10    ASW10          8.E-3     1.0                   STATISTICS
ITCH.     0.10E-01  0.10E-02  0.00E+00  0.00E+00 !76B10    BSW10         10.E-3     1.E-3
ITCH.     0.12E-01  0.10E+01  0.00E+00  0.00E+00 !  C10    CSW10         12.E-3     1.0                   STATISTICS
ANK CARD TERMINATING SWITCH CARDS.               !

TCH PAIR   1          'BSW1  ' TO 'B1    '  AND  'ASW1  ' TO 'A1    '
E          -3.5000 -3.0000 -2.5000 -2.0000 -1.5000 -1.0000 -0.5000  0.0000   0   .0000  1.5000      2.5000  3.0000
PLE         0.0000  0.0000  0.0300  0.0300  0.0700  0.1700  0.3100  0.4800       .8300  0.9200      1.0000  1.0000
CRETICAL    0.0000  0.0013  0.0062  0.0228  0.0668  0.1587  0.3085  0.5000       .8413  0.933       0.9938  0.9987
E
PLE         3.5000  4.0000
CRETICAL    1.0000  1.0000
            0.9998  1.0000
```





1.1b Card for Varying the Printout Frequency (optional)

If and only if parameter 'IPUN' of the second miscellaneous data card is set by the user to value -1 , the following card is to immediately follow the second miscellaneous data card:



This card specifies at what time-step numbers the printout frequency is to be changed, and what values the frequency is to be changed to. Up to five pairs of step numbers and new printout frequencies are permitted, as per the following definitions:

$KCHG_i$ ----- Time-step number at which the i-th variation in the printout frequency is to begin. Printout for this particular step number is always provided, as a beginning to the new frequency of output.

$MULT_i$ ----- Modified value of "IOUT" (see second misc. data card), to begin at time-step number $KCHG_i$.

Pairs must be ordered corresponding to increasing time (increasing "KCHG"). No bounding entry is needed, as the last nonzero pair (if less than the full five pairs) simply remains in effect from the time it commences until the end of the study. The first "KCHG" value, read from columns 1-8, must be positive.

Special time-control of diagnostic printout

Minus signs can be appended to the $MULT_i$ values as defined above, if the user wants to control as a function of time the diagnostic printout of the time-step loop. Recall that diagnostic printout will produce output for every time step; if a large number of steps are taken, astronomical quantities of paper will be consumed ---- unless such printout is selectively controlled as a function of time. The following scheme is used:

a) If a minus sign is appended to MULT(J) , then at step number KCHG(J) the diagnostic printout status will be changed. That is, there will be a switching of the two sets of diagnostic printout control parameters:
   1. (IPRSOV(K), K=16, 19) of Section 1.0g7 ;
   2. (IPR(K), K=1, 4) of Section 1.0g8 .
   For further explanation, refer to the two sections just cited.

b) If there is no minus sign, there will be no change in status of the diagnostic printout at the associated time step.

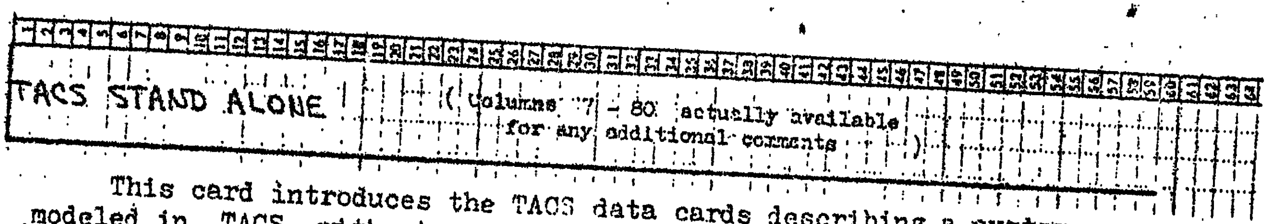
If one or more minus signs are used as just described, it is only the absolute value of $MULT_i$ which controls the production (non-diagnostic) printout frequency as originally described. That is, the use of minus signs does not interfer with the original usage.

1.20 TACS DATA CARDS (IF ANY)

TACS is an acronym derived from the name Transient Analysis of Control Systems. In very general terms, it directly provides the user with modeling capability which is normally associated only with an analog computer, as fully documented in Section 8. . If such modeling is involved in a data case, this present mention is just a reminder that such data is to be physically positioned at this point in the data deck --- before the first EMTP branch card, but after the miscellaneous data cards (and any extensions).

The beginning of TACS data is announced to the EMTP by means of one of the two following special request records:

A)



TACS STAND ALONE

(Columns 7 - 80 actually available for any additional comments)

This card introduces the TACS data cards describing a system modeled in TACS without any associated electric network components. The data case will look as follows:

:

TACS STAND ALONE

[TACS cards (see Section 8.)

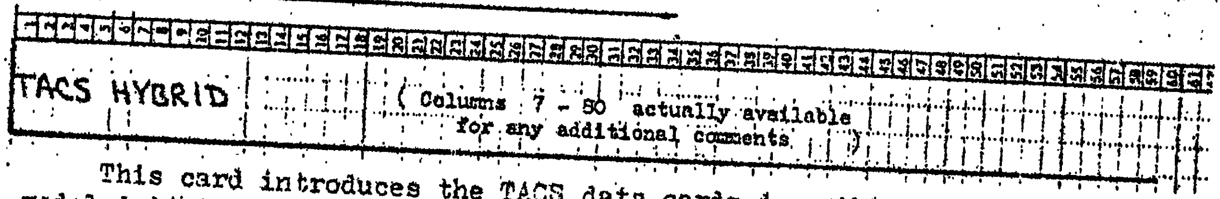
plotting cards (see Section 1.10)

BEGIN NEW DATA CASE

:

-or-

B)



TACS HYBRID

(Columns 7 - 80 actually available for any additional comments)

This card introduces the TACS data cards describing a system modeled in TACS and including components interfaced with associated components of the electric network. The data case will look as follows:

:

TACS HYBRID

[TACS cards (see Section 8.)

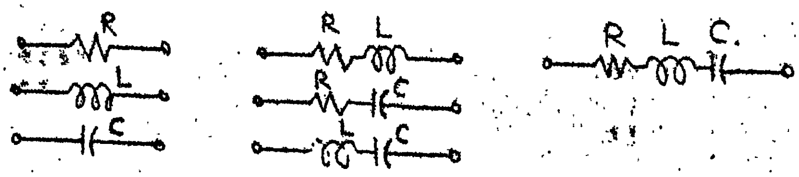
[electric network cards (see Section 1.)

:

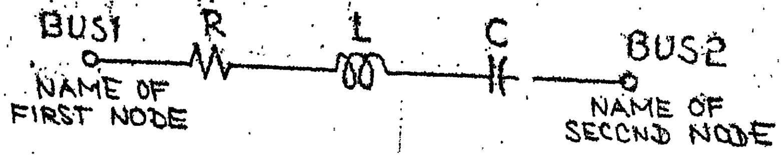
Note: The characters 'TACS OUTPUTS' are also recognized as introducing a TACS hybrid case, for convenience to users of older data cases.

1.21 BRANCH CARD FOR UNCOUPLED, LUMPED, SERIES R-L-C BRANCH

To be used for the following types of branches without coupling:



a) RULES



1) Punch the branch-type "ITYPE" of columns 1-2 as zero or blank.

2) Specify the two terminal nodes of the branch by 6-character alphanumeric node names, using fields "BUS1" and "BUS2" of columns 3-14. One node of the branch may be grounded (field for node name left blank).

3) At least one of the values R, L, C of the branch must be $\neq 0$.

4) When series branch has no R or L, then set R=0 or L=0. When no capacitance, set C=0 (program regards this as $\frac{1}{\omega C} = 0$).

5) If branch data R,L,C are identical with those on a preceding branch card, then the following storage saving option may be used:

Repeat node names of that preceding reference branch in the provided columns 15-26 in the same sequence and leave R,L,C blank.

CAUTION: If the reference branch has other branches in parallel, it is not clear which of them should be the reference branch. Therefore, the first branch among parallel branches with identical node-name pairs shall always be the reference branch. Note that two branches 'NODE-A' to 'NODE-B' and 'NODE-B' to 'NODE-A' do not have identical node-name pairs (order is reversed) and can therefore be used as two distinct reference branches.

6) The numerical values for parameters R , L , and C are in the following units. Recall that variables "XOPT" and "COPT" come from the floating-point (first) miscellaneous data card of Section 1.0h .

a) Specify R in ohms.

b) Specify inductance L as

i) inductance L in mH if XOPT=0.

ii) reactance ωL in ohms at frequency $\frac{\omega}{2\pi}$ = XOPT if XOPT $\neq$ 0.

c) Specify capacitance C_{ij} as

i) capacitance C in μF if COPT=0.

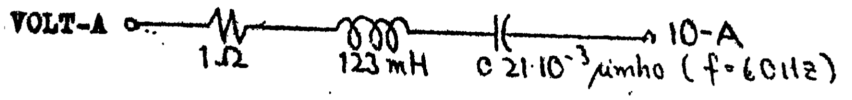
ii) susceptance ωC in μmhos at frequency $\frac{\omega}{2\pi}$ = COPT if COPT $\neq$ 0.

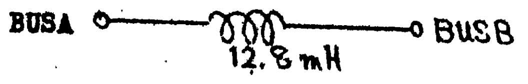
7) Output options for printing and/or plotting:
Punch "1" in column 80 to get branch current;
" "2" " " to get branch voltage,
" "3" " " to get both branch voltage and current;
" "4" " " to get branch power and energy consumption (see details in Section 1.8).

b) **FORMAT & EXAMPLES**

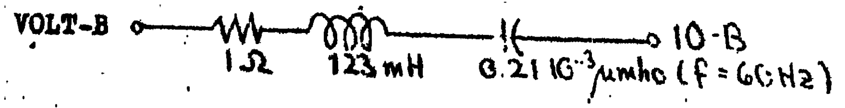
	ITYPE (1–2)	NODE NAMES: BUS1 (3–8)	NODE NAMES: BUS2 (9–14)	NODE NAMES OF REFERENCE BRANCH: BUS3 (15–20)	NODE NAMES OF REFERENCE BRANCH: BUS4 (21–26)	R (Ω) (27–32)	L(mH) or ωL(Ω) (33–38)	C(μF) or ωC(μmho) (39–44)	45 … 79	OUTPUT OPTION (80)
Format :	I2	A6	A6	A6	A6	E6.2	E6.2	E6.2		
Examples	0	VOLT-A	10-A			1.	123.	.21E-3		
	0	BUSA	BUSB				12.8			3
	0	VOLT-B	10-B	VOLT-A	10-A					1
	0	PORT				300.				

Above examples (assuming XOPT=0. and COPT=60.):

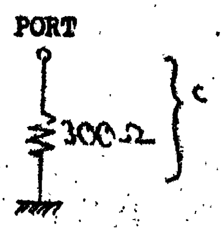




} Current and voltage across branch will be included in output.



} Current through this branch will be included in output



Maximum resistance to use for voltage sampling

Often the user will have occasion to add a very high resistance branch between two nodes the voltage difference between which he is interested in monitoring. But how high a value is permitted? The general rule is that R must not exceed the square root of the largest number which the computer system being used can represent in floating-point form. Specifically, one can use a value of 1.E18 ohms on Univac and Honeywell/GE, 1.E35 ohms on IBM, and 1.E100 ohms on CDC. These are convenient round numbers which should always be legal.

Minimum resistance to use for switch isolation or current sampling

The user often has occasion to input one or more very small resistance or inductance branches, for the purpose of either:

a) the isolation of switches (only one switch may be connected to a node of unknown voltage; see rules of Section 1.4), or

b) the sampling of current in other branches of the network (not all EMTP components permit current output requests using the familiar column-80 punch).

Ideally, a zero-impedance branch would be used, but this is not possible for the EMTP (an attempt to input a zero-impedance branch will yield an EMTP error message). Instead, the user must employ a "small" impedance value, where the minimum permissible or desirable value is a function of several considerations:

Point 1 : The fundamental limitation is due to floating-point word length of the particular EMTP translation version and computer system which the user is working with. For example,

a) The user must be very careful when working with a 32-bit REAL*4 translation of IBM (or other similar byte-oriented machine).

b) Less caution is required for 36-bit translations such as for single-precision Univac or Honeywell/GE.

c) The user is permitted great latitude on CDC, with its 60-bit word, or when working with a 64-bit REAL*8 translation of IBM.

d) Finally, of course, a double-precision translation involving 72-bit words as on Univac or Honeywell/GE allows even more recklessness and carelessness!

Point 2 : Singularity tolerances "EPSILN" and "TOLMAT" (floating-point miscellaneous data parameters; see Section 1.0h) are actually used by the EMTP to protect the user against a too-small impedance value. Parameter "EPSILN" is used for the real, all-resistive transient equivalent-network solution, while "TOLMAT" applies to the complex (phasor) admittance-matrix solution for steady-state initial conditions. The general idea is that all impedances which terminate on a given node should not differ drastically in value, as measured by the just-mentioned singularity tolerances. Specific relevant points related hereto include the following:

a) Considering "EPSILN"., the impedances in question are equivalent Norton resistances which result from trapezoidal-rule integration (see Ref. 1). For a resistor, this is just the value of the resistance in ohms; for an inductor of L Henries, the impedance in ohms is $2L/\Delta t$; for a capacitor of C Farads, the impedance is $\Delta t/2C$. For distributed-parameter transmission lines or cables, treat them like resistors having resistance equal to the characteristic impedance. In the just-stated formulas, Δt is the time-step-size "DELTAT" , in seconds (see Sect. 1.0h).

b) Considering "TOLMAT" , the impedances in question are phasor impedances, depending not only upon the element, but also upon the frequency of the sinusoidal excitation being used. The impedance of a resistor is just the value of the resistance in ohms; for an inductor, use ωL ; for a capacitor, use $1/\omega C$. For distributed-parameter transmission lines or cables, a lumped nominal-Pi approximation is generally valid for usage here, if the line is not too long electrically (maybe 100 or 200 miles at 60 Hz).

Point 3 : For current-sampling purposes, the user is reminded that a permanently closed switch can sometimes be advantageously used in place of a low-impedance branch. See the writeup of Section 1.40 , Class 4 switch ("MEASURING" switch). If a "MEASURING" switch is used, all concern over the question of "how small is small" is avoided --- which may be useful when working on a computer that has limited (marginal) floating-point precision. The solution time for the simulation might possibly increase, however (it all depends on the problem; it also could in some cases actually decrease).

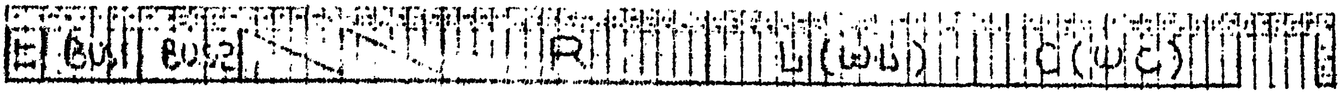
Alternate high-precision format

The $VINTAGE card (see Section 1.-D), which is honored by most computer systems, provides for an alternate high-precision format. Specifically, the R,L,C fields can be switched to 3E16.0 (columns 27-74 in this case) if $VINTAGE, 1 precedes such a group of new branch cards, and $VINTAGE, 0 follows the grouping. As of August 1980, Pi-circuits (Section 1.23) and the original distributed line (Section 1.26) are other components which allow such new, wider formats; they can also be included in the grouping between the $VINTAGE cards, then:

$VINTAGE, 1

Any mixture of series R-L-C, Pi-circuit, and distributed line cards, as long as all use the new wide formats.

$VINTAGE, 0



1.22 [illegible]

I. [illegible]

[illegible] be used only for runs which stop after [illegible] is complete ($t_{\max}$ < 0 , meaning that no [illegible]. For such studies, numerous Pi-circuits [illegible] to represent a total transmission [illegible] occurring at the points of [illegible] series or shunt elements may sometimes [illegible] points, also. The "CASCADED PI" option [illegible], provided the user is only interested [illegible] Use of this feature makes it [illegible] on (i.e., the solution variables) at [illegible] adjacent branches.

[illegible] associated with "CASCADED PI" is worth [illegible] understanding [illegible] efficient usage of this [illegible] components representing the line are [illegible], from one end (the sending end) to the [illegible]. This data is processed as it is read, sequentially, [illegible] of the process a mathematical equivalent for all [illegible] end and the last component read. This is [illegible] 2.

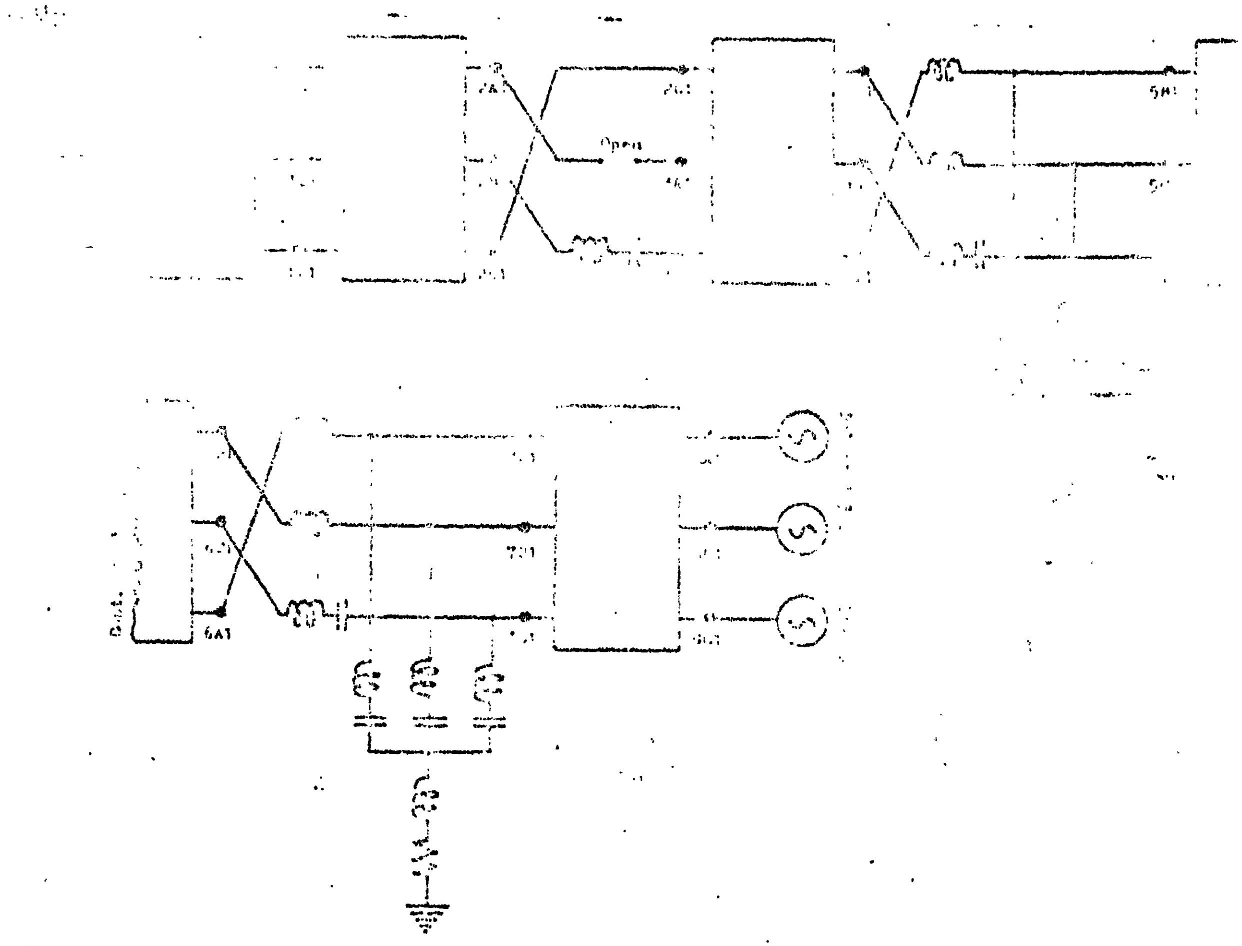


Fig. 1. Sample problem to illustrate usage of the "CASCADED PI" feature. Bus (RA1; RB1 RC1) is the sending end of the line, [illegible] (GA1; GB1; GC1) is the receiving end.

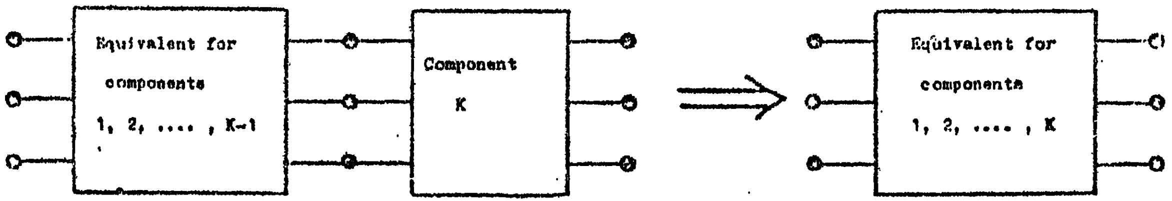


Fig. 2. Schematic illustration of cascading operation for K-th component.

The form of mathematical equivalent used for this is simply the nodal admittance matrix [Y]. Hence when input processing of the last component of the chain is complete, an admittance matrix among the terminal nodes of the line exists, as shown at the right. This is an exact mathematical equivalent for all of the interconnected components of the chain, as seen from the terminal nodes. Matrix [Y] is symmetric and complex (i.e., admittance elements $Y_{km} = G_{km} + jB_{km}$).

$$\begin{array}{c|c|c}
 & \text{Sending} & \text{Receiving} \\
\hline
\text{Sending} & Y_{SS} & Y_{SR} \\
\hline
\text{Receiving} & Y_{RS} & Y_{RR}
\end{array}$$

From the aforementioned description, several points concerning speed and storage requirements associated with this feature may be deduced:

Point 1: The storage requirement (for [Y]) varies as the square of the number of transmission line conductors; it is independent of the number of components which are cascaded together.

Point 2: Computational effort to produce the equivalent is proportional to the number of components which are cascaded together. The computer time associated with this effort adds to the "data input" time figure of the summary case-termination statistics, not to the time figure for the steady-state solution.

II. Some More-Specific Comments about "CASCADED PI"

Before detailing the specific format of data input for the "CASCADED PI" feature, a few additional comments about restrictions and/or assumptions might be mentioned. Fig. 1 shows a sample problem, the Section-IV setup of which illustrates some of these points:

1. The first line segment of the chain of elements which are to be cascaded may not have any series or shunt connections. That is, the sending end must begin with a Pi-circuit.

2. Second and later sections can each consist of up to four types of sub-components, as follows, in the order shown:

    a) Series uncoupled R-L-C branches, if any.

    b) Shunt uncoupled R-L-C branches, if any.

    c) New line-position (thought of conceptually as transposition) specification, if any.

d) Specification of new (i.e., changed) Pi-circuit parameter matrices [R], [L], and [C].

In order to utilize the "CASCADED PI" modeling feature as part of an EMTP data case, the following classes of data are involved, in the order indicated:

Class 1 : "CASCADED PI" header card (i.e., special request card which begins the definition process.

Class 2 : Cards which specify the sending end and receiving end bus names, as well as the [R], [L], and [C] matrices which apply to the first Pi-circuit.

Class 3 : Line position card for the first Pi-circuit, the one at the sending end of the line.

repeated

Class 4 : Line position card, if any.

Class 5 : Cards defining series R-L-C branches, if any.

Class 6 : Cards defining shunt R-L-C branches, if any.

Class 7 : Cards specifying new [R], [L], and [C] parameter matrices, if any.

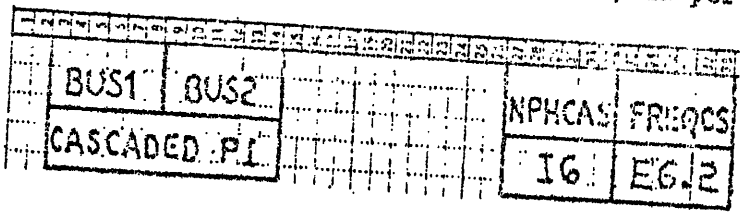
Class 8 : "STOP CASCADE" card, to close the definition process.

Classes 1, 2, 3, and 8 are used only once, for the sending and the receiving end of the line in question. Classes 4, 5, 6, and 7 apply to the interior of the line, to be repeated over and over again, once for each section.

III. Format and Meaning of Different Classes of Data for "CASCADED PI"

Class 1 : "CASCADED PI" header card

One begins the definition process for a line by means of the special request card having "CASCADED PI" punched in columns 3-14, as per the following format:



Cols. 3-14 Punched with the key request word "CASCADED PI".

Cols. 27-32 Variable "NPHCAS", the number of phases or conductors in the circuit to be cascaded. The maximum permissible number is dependent upon user EMTP dimensioning (see Section C.6) ; execution should terminate with an overflow error message, if the user attempts to represent a line having too many conductors.

Cols. 33-38 Variable "FREQCS", the frequency in Hz of the sinusoidal steady-state phasor solution which is to be performed.

Class 2 : Specification of bus names, matrices [R], [L], [C]

These data cards are for inputing the sending-end and receiving-end bus names of the line, plus the [R], [L], and [C] matrices which characterize the line geometry of the first section. The format is identical to that which is used for a conventional Pi-circuit:

ITYPE	Node Names		Reference br.		elements (k,m)			elements (k,m+1)			elements (k,m+2)		
	BUS1	BUS2	BUS3	BUS4	R	L	C	R	L	C	R	L	C
I2	A6	A6	A6	A6	E6.2	E6.2	E6.2	E6.2	E6.2	E6.2	E6.2	E6.2	E6.2

Rule 1: Number the phases 1, 2, . . . NPHCAS. Make out one branch card plus possible continuation cards, (See Rule 6) for each phase and stack them in this sequence. Indicate this sequence by punching 1, 2, . . . NPHCAS in columns 1-2 of these cards (field ITYPE). These numbers will be referred to later as the line position number for this base matrix.

Rule 2: Specify the circuit consisting of NPHCAS phases by the names of the nodes at both ends (use columns 3-14; field names BUS1, BUS 2). Nodes may be grounded (indicated by blank field name) if desired. These names do not necessarily correspond to the R-L-C matrix values on the same card. The line position card takes care of the relation between bus name and R-L-C matrix values.

Rule 3: At least one of the matrices [R], [L] must be nonzero. Matrix [C] may be zero. Specifically, $[R] + j\omega[L]$ must be non-singular.

Rule 4: If this cascaded pi circuit is identical with another cascaded pi circuit then the following storage-saving option may be used:

Repeat node names of the first branch of that preceding set of branch cards in the provided columns 15-26 of the first branch in the same sequence and leave R, L, C blank. On the 2nd, 3rd, . . . NPHCAS-th branch card only the information in columns 1-14 is used.

CAUTION: 1) Same as in rule 5 of section 1.21.
2) Rule 1 & 2 of this section do not necessarily hold. Rule 1 & 2 of section 1.23 are more pertinent.

NOTE: The program will properly process the reference data with or without the CASCADED PI header card and STOP CASCADE terminator card. Care must be taken that either both or none of these cards should appear.

Rule 5: The numerical values for [R], [L], and [C] are in the following units. Recall that variables XOPT and COPT come from the floating-point miscellaneous data card (see Section 1.0h).

a) Specify R_{ij} in ohms

b) Specify inductances L_{ij} as

1) inductance L in mH if XOPT=0.

ii) reactance ωL in ohms at frequency $\frac{\omega}{2\pi} =$ XOPT if XOPT $\neq 0$.

c) Specify capacitances C_{ij} as

i) capacitance C in μF if COPT $= 0$.

ii) susceptance ωC in μmhos at frequency $\frac{\omega}{2\pi} =$ CCPT if COPT $\neq 0$.

Rule 6: Matrices [R], [L], and [C] are symmetric, so only need be specified on and below the diagonal. The following format applies:

1	Node names of 1st branch		R_{11}	L_{11}	C_{11}						
2	Node names of 2nd branch		R_{21}	L_{21}	C_{21}	R_{22}	L_{22}	C_{22}			
3	Node names of 3rd branch		R_{31}	L_{31}	C_{31}	R_{32}	L_{32}	C_{32}	R_{33}	L_{33}	C_{33}
4	Node names of 4th branch		R_{41}	L_{41}	C_{41}	R_{42}	L_{42}	C_{42}	R_{43}	L_{43}	C_{43}
			R_{44}	L_{44}	C_{44}						
5	Node names of 5th branch		R_{51}	L_{51}	C_{51}	R_{52}	L_{52}	C_{52}	R_{53}	L_{53}	C_{53}
			R_{54}	L_{54}	C_{54}	R_{55}	L_{55}	C_{55}			

⋮ etc.

Rule 7: No branch voltage output, or branch current output, is possible for this component, so don't put any of those special punches in col. 80. Of course the complete steady-state solution will show all branch flows.

Class 3 : Line position card for sending-end section

The line position card is used to specify control parameters pertaining to the associated line section and lumped elements. As used for Class 3 data, it applies only to the very first segment, the beginning of the cascading process. The general definition is contained in the Class 4 data explanation which follows.

Class 4 : Line position card

The line position card is used to specify control parameters pertaining to the associated line section and lumped elements. The following format applies:

	DSECTJ	MULTIP	MSER	MBR	MSECT	Phase-location indicator MAPCAS(I)			
						Phase 1	Phase 2	Phase 3	Etc. for all phases • • • • (MAPCAS(I), I=1, NPHCAS)
	E6.2	I4	I4	I4	I4	I4	I4	I4	• • • •

Rule 1: Length of segments is specified by DSECTJ. This is a per unit length where the base length is determined by the length of line represented by the equivalent pi matrix. That is the length of the line represented by this matrix is 1.0.

Example: If a 5 mile length of line is needed for a section and the R-L-C equivalent pi matrix is per mile then DSECTJ = 5.0. However, if the R-L-C equivalent pi matrix is for a 5 mile length of line, then DSECTJ = 1.0.

Rule 2: If N identical sections are to be cascaded together without any transpositions, then MULTIP can be set to N rather than include N line position cards. There may be series and shunt connections between these sections, but these connections must be the same for all sections handled by this multiplicity feature. Default value of 1 if MULTIP is left blank.

Rule 3: Specification of series connection

MSER=1 This indicates that there is a R-L-C series connection for this section(s) and data for this is to follow.

MSER=0 This indicates that there is no R-L-C series connection for this section(s).

MSER=-1 This indicates that there is a R-L-C series connection for this section(s). The data from the last R-L-C series connection is to be used.

Comment: Should the user desire to put the same R-L-C connection between every other section this can be easily accomplished as follows:

The first section preceeded by the R-L-C series connection would have MSER=1. The next section would have MSER=0. The third section, which is to be preceeded by a R-L-C series connection would have MSER=-1.

Rule 4: Specification of R-L-C shunt connections MBR=1, 0, -1 has same meaning for shunt R-L-C connections as MSER has for series connections.

Rule 5: Specification of line-section parameters R, L, and C

MSECT= 0 or blank means old R-L-C values are used for following section(s).

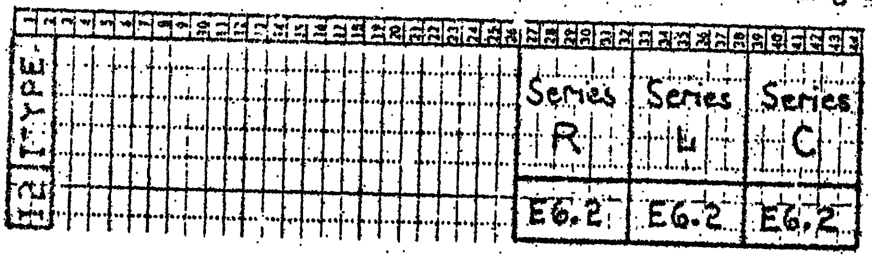
MSECT= 1 a new R-L-C matrix is to be read in

Rule 6: Specification of line position. These numbers are a map of the position of the phases of the cascaded circuit. The fields across the card starting in column 25 correspond to the phases in the order their names appear in the BUS1, BUS2 fields on the NPHCAS equivalent pi cards. The number entered in these fields are the row number of the R-L-C equivalent pi matrix. Thus if the conductor connecting the nodes specified by the first equivalent pi card BUS1-BUS2 field has electrical properties which are specified by the third row of the R-L-C matrix then a 3 would be put in column 28.

For 14 or fewer conductors, cols. 25-80 of the data card suffice, as shown. But for 15 or more conducters, the MAPCAS(I) data spills over onto as many extra cards of the format 24X, 14I4 as are required to complete the data input.

Class 5 : Series R-L-C branch specification

Class 5 data consists of series R-L-C branches, connected in series with any particular conductor (phase) of the line. The following format applies:



Rule 1: Field ITYPE of columns 1-2 is to be punched with the conductor number which the R-L-C branch being defined is to be placed in series with.

Rule 2: If a short circuit is desired, simply do not enter a data card of this class for that conductor.

Rule 3: If an open circuit is desired, punch field R of columns 27-32 with "999999" —— to be interpreted by the EMTP as a special flag meaning "open circuit".

Rule 4: At least one of the parameter values R , L , or C of the card must be nonzero.

Rule 5: If the desired branch has no resistance, set R equal to zero (or leave blank); if the branch has no inductance, set L equal to zero (or leave blank); if the branch has no capacitance, set C equal to zero (or leave blank), which is interpreted by the EMTP as though series capacitance C were actually infinite, a capacitive short circuit.

Rule 6: The numerical values for R , L , and C are in the following units. Recall that variables XOPT and COPT come from the floating-point miscellaneous data card (see Section 1.0h).

a) Specify R_{ij} in ohms

b) Specify inductances L_{ij} as

  i) inductance L in mH if $XOPT = 0$.

  ii) reactance ωL in ohms at frequency $\frac{\omega}{2\pi} = XOPT$ if $XOPT \neq 0$.

c) Specify capacitances C_{ij} as

  i) capacitance C in μF if $COPT = 0$.

  ii) susceptance ωC in μmhos at frequency $\frac{\omega}{2\pi} = COPT$ if $COPT \neq 0$.

Rule 7: The end of such series R-L-C branch cards is signaled by a blank card.

Class 6 : Shunt R-L-C branch specification

Series R-L-C branches may be connected in shunt, thereby being categorized as shunt R-L-C branches of data class number 6. This is illustrated by the Fig. 1 schematic diagram, at busses 7A1 , 7B1 , and 7C1 . The shunt branches in question can be connected between any two nodes which are either conductor nodes or intermediate extra nodes, including local ground. The applicable format and rules for such shunt R-L-C branches are as follows:

Terminal node numbers			Branch parameter values		
N1	N2		R	L	C
I6	I6		E6.2	E6.2	E6.2

Rule 1: Fields N1 and N2 are to be punched with node numbers. If one wants a conductor, the associated node number is the positive integer (row or column number) assigned to it in the line-parameter matrices R , L , and C . Zero or blank is reserved for local ground. Any other new, intermediate nodes are given consecutive negative integer values -1, -2, etc. for as many as are needed. Such numbering is local to the line section in question, with one beginning over again with -1 the next time. A limit of "NPHCAS" such intermediate nodes for each section exists (i.e., not more than one for each conductor).

Rule 2: At least one of the parameter values R , L , or C of each branch must be nonzero.

Rule 3: If the desired branch has no resistance, set R equal to zero (or leave blank); if the branch has no inductance, set L equal to zero (or leave blank); if the branch has no capacitance, set C equal to zero (or leave blank), which is interpreted by the EMTP as though series capacitance C were actually infinite, a capacitive short circuit.

Rule 4: The numerical values for R , L , and C are in the following units. Recall that variables XOPT and COPT come from the floating-point miscellaneous data card (see Section 1.0h).

a) Specify R_{ij} in ohms

b) Specify inductances L_{ij} as

   i) inductance L in mH if XOPT = 0.

   ii) reactance ωL in ohms at frequency $\frac{\omega}{2\pi} = \text{XOPT}$ if XOPT $\neq 0$.

c) Specify capacitances C_{ij} as

   i) capacitance C in μF if COPT = 0 .

   ii) susceptance ωC in μmhos, at frequency $\frac{\omega}{2\pi} = \text{COPT}$ if COPT $\neq 0$.

Rule 5: The end of such shunt R-L-C branch cards is signaled by a blank card.

Class 7 : Change of line parameters [R], [L], and [C]

During the cascading process, the line geometry can be altered if desired, which necessitates the redefinition of matrices [R], [L], and [C] . If this is the case, field "REACT" of the associated line-position card (Class 4 data) must have been punched with value "1" . The general data format for Class 7 input then is like that of Class 2, with the following exceptions:

a) Rules 2 and 4 of the Class 2 data description do not apply. There are no bus names "BUS1" and "BUS2" to be inputted, so leave columns 3-14 blank. No storage-saving option is possible, so likewise enter nothing in cols. 15-26.

Class 8 : Termination of Cascaded-PI data

The last card in the definition sequence for a line which is being modeled using "CASCADED PI" is a record reading "STOP CASCADE" , as per the following format:

```
STOP CASCADE
```

This card tells the EMTP that it has now processed all sections making up the line which connects the sending-end and receiving-end busses which were defined on the Class 2 data input.

IV. Illustrative Sample Usage of "CASCADED PI" Feature

Fig. 1 displays a sample network for which the steady-state sinusoidal phasor solution can be found in two different ways: first, using the conventional, manual EMTP data setup, and second using the "CASCADED PI" modeling capability just described. Listings of these two alternative data case setups for this problem are shown below:

```
BEGIN NEW DATA CASE
C      UTPF TEST CASE NO. 19
C      CHECK CASE FOR THE SAMPLE SMALL STEADY-STATE PROBLEM WHICH
C      ILLUSTRATES MANY FEATURES OF THE "CASCADED PI" CAPABILITY OF THE T.P.
C      THIS CASE IS COMPLETELY SET UP MANUALLY, WITHOUT ANY USE OF THE
C      "CASCADED PI" OPTION.    THE ANSWERS SHOULD BE IDENTICAL, OF COURSE.
         0       0    60.
                                      1        1
  1RA1    1A1                          .877  8.40 .1625
  2RB1    1B1                          .747  4.14-.0252  .857  8.43 .1559
  3RC1    1C1                          .735  3.47-.0067  .723  4.17-.0277  .829  8.46 .1971
  11A1    2A1    RA1    1A1
  21B1    2B1
  31C1    2C1
  02B1    3B1                                13.1449.071
  13C1    4C1    RA1    1A1
  23A1    4A1
  33B1    4B1
  04C1    5C1                                13.14
  04A1    5A1                                13.1449.071
  04B1    5B1    4C1    5C1
  05C1    5G1    2B1    3B1
  05A1    5G1    2B1    3B1
  05B1    5G1    2B1    3B1
          5G1                            5.0 13.14
  15B1    6B1    RA1    1A1
  25C1    6C1
  35A1    6A1
  06A1    7A1    4B1    5B1
  06B1    7B1    4C1    5C1
```

7i

```
  6C1   7C1   4A1   5A1
  7A1   7G1   2B1   3B1
  7B1   7G1   2B1   3B1
  7C1   7G1   2B1   3B1
        7G1         5G1
 17A1   GA1                 1.658 16.92 .3162
 27B1   GB1                 1.446  8.34-.0554 1.704 16.86 .3118
 37C1   GC1                 1.470  6.94-.0134 1.494  8.28-.0504 1.754 16.80 .3256

14GA1      424.35     60.          0.0                      -.1
14RA1      424.35     60.         10.0                      -.1
14GB1      424.35     60.       -120.0                      -.1
14RB1      424.35     60.       -110.0                      -.1
14GC1      424.35     60.        120.0                      -.1
14RC1      424.35     60.        130.0                      -.1

BEGIN NEW DATA CASE
C     UTPF TEST CASE NO. 10
C     SAMPLE SMALL STEADY-STATE PROBLEM WHICH ILLUSTRATES MANY FEATURES OF THE
C     "CASCADED PI" CAPABILITY OF THE T.P. ----- TRANSPOSITION, CASCADING
C     OF PI-CIRCUITS, THE CONNECTION OF SERIES BRANCHES, THE CONNECTING OF
C     SHUNT BRANCHES.
      0       0     60.
                       1         1                                           3
  CASCADED PI                    3 60.0
 1RA1   GA1                  .877  8.40 .1628
 2RB1   GB1                  .747  4.14-.0252  .852  8.43 .1559
 3RC1   GC1                  .735  3.47-.0067  .723  4.17-.0277  .829  8.46 .1571
     1.0   2   0   0   1   1   2   3
     1.0   1   1   0   0   2   3   1
 2                          999999
 3                                  13.1449.071

     1.0   1   1   1   0   3   1   2
 1                                  13.14
 2                                  13.14
 3                                  13.1449.071

       1    -1                      13.1449.071
       2    -1                      13.1449.071
       3    -1                      13.1449.071
            -1                  5.0 13.14

     2.0   1  -1  -1   1   1   2   3
 1                           .829  8.46 .1571
 2                           .723  4.17-.0277  .852  8.43 .1559
 3                           .735  3.47-.0067  .747  4.14-.0252  .877  8.40 .1628
  STOP CASCADE

14GA1      424.35     60.          0.0                      -.1
14RA1      424.35     60.         10.0                      -.1
14GB1      424.35     60.       -120.0                      -.1
14RB1      424.35     60.       -110.0                      -.1
14GC1      424.35     60.        120.0                      -.1
14RC1      424.35     60.        130.0                      -.1

BEGIN NEW DATA CASE
```

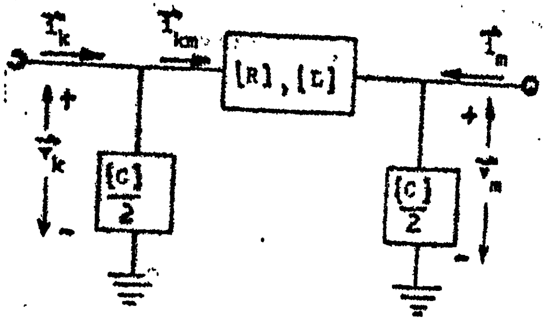
1.23 BRANCH CARDS FOR PI-EQUIVALENTS

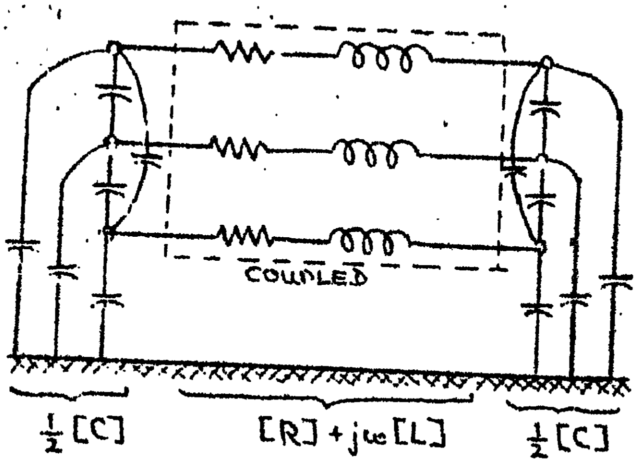
This class of branches provides for the representation of lumped-element resistance, inductance, and capacitance matrices. For N conductors, the associated differential equations are:

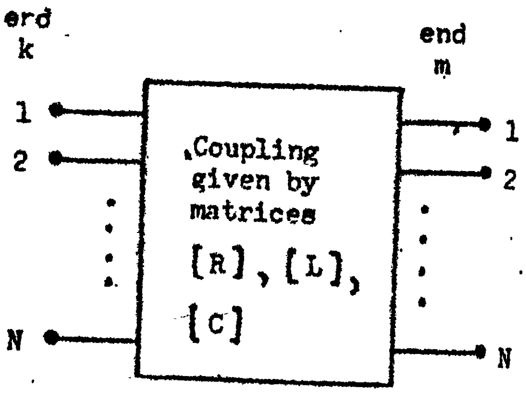
$$\vec{v}_k - \vec{v}_m = [L]\frac{d\vec{i}_{km}}{dt} + [R]\vec{i}_{km}$$

$$\vec{i}_k = \frac{1}{2}[C]\frac{d\vec{v}_k}{dt} + \vec{i}_{km}$$

$$\vec{i}_m = \frac{1}{2}[C]\frac{d\vec{v}_m}{dt} - \vec{i}_{km}$$



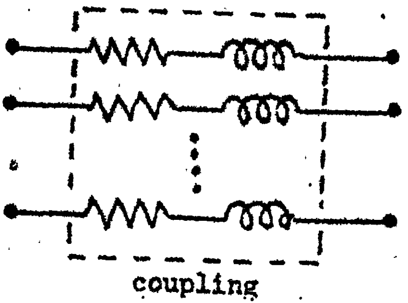




All matrices are assumed to be symmetric, and it will be noted that [C] is split in two, with half of the total on each end of the branch.

Principal use of this model at BPA is to represent short, untransposed sections of transmission line, for which the perfect-transposition assumption of distributed-parameter representation (Section 1.26) is not acceptable. By connecting many such short sections in series, keeping track of actual transpositions (if any), a model for a long line can be made. For such use, the matrices [R], [L], and [C] can be automatically calculated by the BPA line constants program.[5] Yet because of increased running time and core-storage requirements, this modelling should generally be used only as a last resort, where distributed-parameter lines are believed to be inadequate. Refer to further discussion in Section 3.3 .

While [C] = [0] (no capacitance) is a legal input option, this special situation represents only mutually-coupled R-L branches, for which the separate input format of Section 1.24 has been provided.



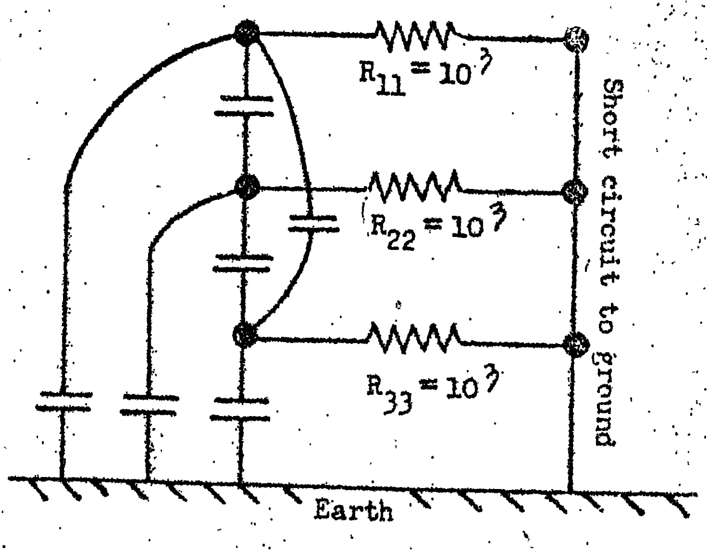
If the user wants just a multiphase ($N \geq 2$) capacitance matrix to ground, then h can input a near-infinite-impedance series branch, and ground all conductors at the far end. In particular, set

$R_{ii} = 10^{?}$ for all i

$R_{ij} = 0$ for $i \neq j$

$[L] = [0]$

$[C]$ = twice the desired final matrix, since it will be halved, remember.



H re ? is a "large" exponent, ideally infinite; In practice it is limited by the computer installation being used. Refer to discussion of high-impedance branches, Section 1.21 .

Elements of the matrices $[R]$, $[L]$, and $[C]$ have the following meaning in the sinusoidal steady state at frequency ω:

diagonal $R_{ii} + j\omega L_{ii}$ = self impedance of branch i (impedance of loop "branch i--ground return"); off-diagonal $R_{ik} + j\omega L_{ik}$ = mutual impedance between branches i and k. ($R_{ik} \neq 0$ with nonzero ground resistivity)

diagonal C_{ii} = sum of all capacitances connected to the nodes at both ends of branch i; off-diagonal C_{ik} = negative value of capacitance from branch i to branch k.

Data format for data cards

To specify an N-conductor Pi-equivalent, the following rules and format are to be observed:

ITYPE	Node Names		Reference br.		elements (k,m)			elements (k,m+1)			elements (k,m+2)		
	BUS1	BUS2	BUS3	BUS4	R	L	C	R	L	C	R	L	C
I2	A6	A6	A6	A6	E6.2	E6.2	E6.2	E6.2	E6.2	E6.2	E6.2	E6.2	E6.2

Rule 1: Number the phases 1, 2, ..., N. Make out one branch card (plus possible continuation cards; see Rule 6) for each phase, and stack them in this sequence. Indicate this sequence by punching 1, 2, ... , N in columns 1-2 of these cards (field ITYPE). Limits on N are $1 \leq N \leq 40$.

Rule 2: Specify each of the phases 1, 2, ... , N by the names of the nodes at both ends (use columns 3-14; field names BUS1, BUS2). Nodes may be grounded (indicated by blank field name) if desired.

Rule 3: At least one of the matrices $[R]$, $[L]$ must be nonzero. Matrix $[C]$ may be zero, though then the Section 1.24 input can be used.

Rule 4: If branch data are identical with those on a preceding set of N branch cards, hen the following storage-saving option may be used:

Re: node names of the first branch of that preceding set of
cards in the provided columns 15-26 of the first branch
ne same sequence and leave R,L,C blank. On the 2nd, 3rd,
.,N-th branch card only the information in columns 1-14 is
ed.

CAUTION: Same as in rule 5 of section 1.21.

The numerical values for $[R]$, $[L]$, and $[C]$ are in the following units. Recall that variables XOPT and COPT come from the floating-point miscellaneous data card of Section 1.04 .

a) Specify R_{ij} in ohms

b) Specify inductances L_{ij} as

   i) inductance L in mH if XOPT = 0.

   ii) reactance ωL in ohms at frequency $\frac{\omega}{2\pi} = XOPT$ if XOPT $\neq 0$.

c) Specify capacitances C_{ij} as

   i) capacitance C in μF if COPT = 0 .

   ii) susceptance ωC in μmhos at frequency $\frac{\omega}{2\pi} = COPT$ if COPT $\neq 0$.

Rule 6: Matrices $[R]$, $[L]$, and $[C]$ are symmetric, so only need be specified on and below the diagonal. The following format applies:

1	Node names of 1st branch		R_{11}	L_{11}	C_{11}						
2	Node names of 2nd branch		R_{21}	L_{21}	C_{21}	R_{22}	L_{22}	C_{22}			
3	Node names of 3rd branch		R_{31}	L_{31}	C_{31}	R_{32}	L_{32}	C_{32}	R_{33}	L_{33}	C_{33}
4	Node names of 4th branch		R_{41}	L_{41}	C_{41}	R_{42}	L_{42}	C_{42}	R_{43}	L_{43}	C_{43}
			R_{44}	L_{44}	C_{44}						
5	Node names of 5th branch		R_{51}	L_{51}	C_{51}	R_{52}	L_{52}	C_{52}	R_{53}	L_{53}	C_{53}
			R_{54}	L_{54}	C_{54}	R_{55}	L_{55}	C_{55}			

⋮ etc.

When one card is not sufficient for all required R-L-C values (for the fourth and later phases), then "continuation cards" are used, with columns 1-26 left blank, it will be noted.

Rule 7: No branch current output is possible for this branch type. However, the branch voltage can be obtained on the first two phases (where column 80 of the card is not being used) by punching a "2" in column 80.

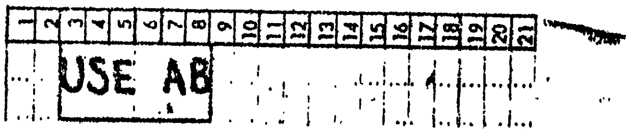
Alternative performance equation for series segment of Pi-circuit

Instead of describing the series leg of a multi-conductor ($N \geqslant 2$) Pi-circuit by means of matrices [R] and [L] , the user may prefer to use arrays [A] and [B] , defined by the alternative performance equation

$$\frac{d\vec{i}_{km}}{dt} = [A]\cdot(\vec{v}_k - \vec{v}_m) + [B]\vec{i}_{km}$$

If this be the case, he then can use the following procedure:

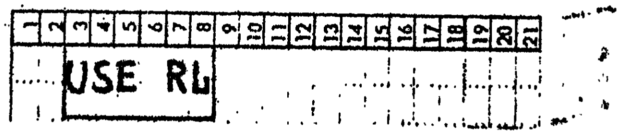
Rule 8: Immediately preceding all mutually coupled branches (note plural; $N \geqslant 2$) for which the AB-option is desired, insert an extra data card with the code "USE AB" punched in what is normally the BUS1-field

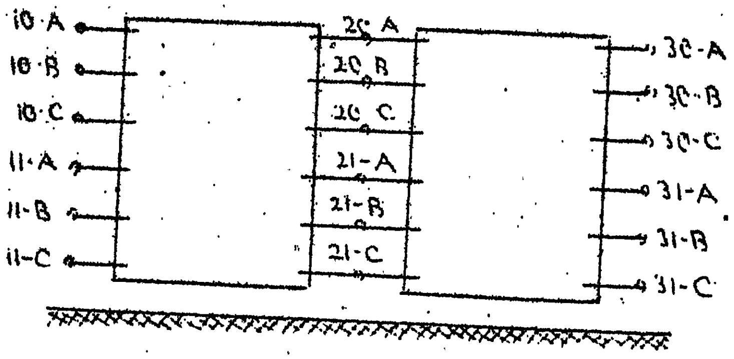


Rule 9: For all multi-conductor coupled circuits in question, punch the elements of [A] where those of [R] would normally appear, and those of [B] instead of [L] :

$$[R] \xrightarrow{\text{becomes}} [A] \qquad\qquad [L] \xrightarrow{\text{becomes}} [B]$$

Rule 10: To return to the use of [R] and [L] after having used [A] and [B] , insert an extra data card with the code "USE RL" punched in what is normally the BUS1-field. For all data following this card, then, use of the R-L formulation is assumed ---- until another "USE AB" card should be encountered.





Example

Consider the modelling of two 3-phase circuits on the same right of way, so that they are mutually coupled. Together these two circuits constitute six coupled conductors ($N = 6$). With two identical Pi-equivalents cascaded, the data cards appear as follows:

BRANCH SEQUENCE	NODE NAMES		NODE NAMES OF REFERENCE BRANCH		[R], [L]- and [C]- MATRICES (in and below diagonal)								
	LEFT NODE	RIGHT NODE	LEFT NODE	RIGHT NODE	R (Ω)	L (mH) or ωL (Ω)	C (μF) or ωC (μmho)	R (Ω)	L (mH) or ωL (Ω)	C (μF) or ωC (μmho)	R (Ω)	L (mH) or ωL (Ω)	C (μF) or ωC (μmho)
I2	A6	A6	A6	A6	E6.2	E6.2	E6.2	E6.2	E6.2	E6.2	E6.2	E6.2	E6.2
Example													
1	10-A	20-A			1.41	8.334	.164						
2	10-B	20-B			0.97	2.8586	-.0289	1.23	9.1392	.1626			
3	10-C	20-C			0.91	2.2823	-.0088	0.86	3.4218	-.0273	1.16	9.518	.1662
4	11-A	21-A			1.00	2.0984	-.0180	0.94	2.1248	-.0101	0.90	2.0398	-.0053
5	11-B	21-B			1.41	8.334	.164						
					0.94	2.1248	-.0101	0.89	2.5064	-.0104	0.86	2.6454	-.0087
6	11-C	21-C			0.97	2.8586	-.0289	1.23	9.1392	.1626			
					0.90	2.0398	-.0053	0.86	2.6454	-.0087	0.83	3.1597	-.0142
1	20-A	30-A	10-A	20-A	0.91	2.2823	-.0088	0.86	3.4218	-.0273	1.16	9.518	.1662
2	20-B	30-B											
3	20-C	30-C											
4	21-A	31-A											
5	21-B	31-B											
6	21-C	31-C											

DATA FOR MULTIPHASE π-EQUIVALENTS:

$$[R] = \begin{bmatrix} 1.41 & & & & & \\ 0.97 & 1.23 & & \text{symmetric!} & & \\ 0.91 & 0.86 & 1.16 & & & \\ 1.00 & 0.94 & 0.90 & 1.41 & & \\ 0.94 & 0.89 & 0.86 & 0.97 & 1.23 & \\ 0.90 & 0.86 & 0.83 & 0.91 & 0.86 & 1.16 \end{bmatrix} \Omega ; \quad \underset{\text{at } 60\,\text{Hz}}{[\omega L]} = \begin{bmatrix} 8.3340 & & & & & \\ 2.8586 & 9.1392 & & & & \\ 2.2823 & 3.4218 & 9.5180 & & \text{symmetric!} & \\ 2.0984 & 2.1248 & 2.0398 & 8.3340 & & \\ 2.1248 & 2.5064 & 2.6454 & 2.8586 & 9.1392 & \\ 2.0398 & 2.6454 & 3.1597 & 2.2823 & 3.4218 & 9.5180 \end{bmatrix} \Omega$$

$$[C] = \begin{bmatrix} 0.1640 & & & & & \\ -0.0289 & 0.1626 & & & \text{symmetric!} & \\ -0.0088 & -0.0273 & 0.1662 & & & \\ -0.0180 & -0.0101 & -0.0053 & 0.1640 & & \\ -0.0101 & -0.0104 & -0.0087 & -0.0289 & 0.1626 & \\ -0.0053 & -0.0087 & -0.0142 & -0.0088 & -0.0273 & 0.1662 \end{bmatrix} \mu F$$

Alternate high-precision format

The $VINTAGE card (see Section 1.-D), which is honored by most computer systems, provides for an alternate high-precision format. Specifically, the R,L,C fields can be switched to 3E16.0 (columns 27-74 in this case) if $VINTAGE, 1 precedes such a group of new branch cards, and $VINTAGE, 0 follows the grouping. Here only one triplet of (R, L, C) values is allowed on each data card, of course. For the second and later rows, ordering is from left to right (e.g., the card for column 2 follows that for column 1, etc.). Series R-L-C branches (Section 1.21) and the original distributed line (Section 1.26) are other components which allow such new, wider formats; they can also be included in the grouping between the $VINTAGE cards, then:

$VINTAGE, 1

> Any mixture of series R-L-C, Pi-circuit, and distributed line cards, as long as all use the new wide formats.

$VINTAGE, 0

To remove any ambiguity as to the format, the following diagram corresponds to the case of narrow format as illustrated under Rule 6 (see three or so pages before):

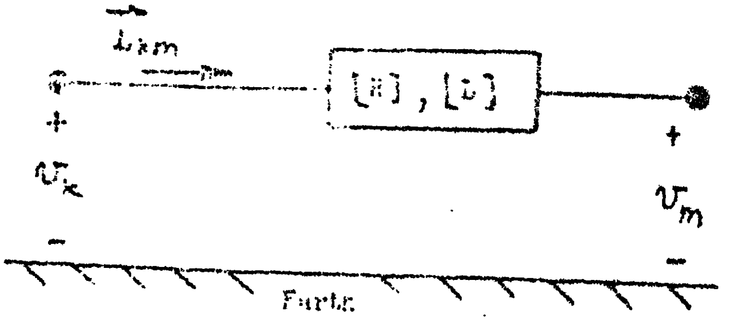
1	SA	RA	R_{11}	L_{11}	C_{11}
2	SB	RB	R_{21}	L_{21}	C_{21}
			R_{32}	L_{22}	C_{22}
3	SC	RC	R_{31}	L_{31}	C_{31}
			R_{32}	L_{32}	C_{32}

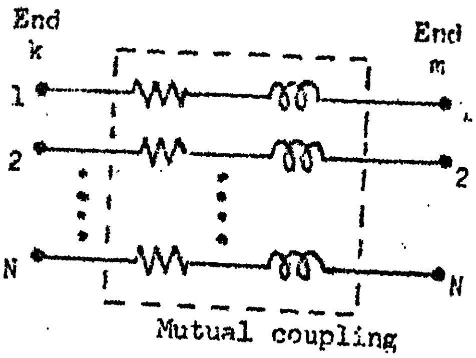
⋮ Etc.

[illegible] Branch Card for Mutually-Coupled R-L Elements

This class of branches provides for the representation of lumped-element, mutually-coupled R-L branches. Associated with these branches are matrices [L] and [R] having performance equations

$$\vec{v}_k - \vec{v}_m = [L]\frac{d\vec{i}_{km}}{dt} + [R]\vec{i}_{km}$$





Matrices [R] and [L] are assumed to be symmetric.

Note that this branch type is identical in performance to the Pi-equivalent of Section 1. [illegible], if the user therein sets the capacitance matrix [C] to zero. But in the present section the inductance data fields (see below) have 12 columns rather than just 6, allowing for greater precision. This option is intended to be used primarily for coupled impedances representing transformers, wherein it is necessary to have highly-accurate values for self and mutual impedances; otherwise the leakage impedances get lost in the magnetizing impedance. See Section 6. for a discussion of transformer representation.

Data format for data cards

To specify N mutually-coupled R-L elements, the following rules and format are to be observed:

	Node Names				elements (k,m)		elements (k,m+1)		elements (k,m+2)	
[illegible]	BUS1	BUS2	BUS3	BUS4	R	L	R	L	R	L
I2	A6	A6	A6	A6	E6.2	E12.2	E6.2	E12.2	E6.2	E12.2

Rule 1: Number the phases 51, 52, ..., (50+N). Make out one branch card (plus possible continuation cards; see Rule [illegible]) for each phase, and stack them in this sequence. Indicate this sequence by punching 51, 52, ..., (50+N) in columns 1-2 of these cards (field ITYPE). Limits on N are $1 \leq N \leq 40$.

Rule 2: Specify each of the phases 51, 52, ..., (50+N) by the names of the nodes at both ends (see columns 3-14; field names BUS1 and BUS2). Nodes may be grounded (indicated by blank field name) if desired.

Rule 3: If branch data are identical with those on a preceding set of N branch cards, then the following storage-saving option may be used:

Repeat the node names of the first branch of that preceding set of branch cards in columns 15-26 (fields BUS3 and BUS4) of the first branch in the same sequence of this new group, and leave R and L fields blank. On the 2nd, 3rd, ... , N-th branch card, only the information in columns 1-14 (ITYPE, BUS1, BUS2) is used.

CAUTION: As the reference branch is only identified by an ordered pair of node names, ambiguity is possible. If more than one candidate fulfills this description (of 2 or more parallel branches), then the program simply chooses the first such branch inputted. Note that two branches 'NODE-A' to 'NODE-B' and 'NODE-B' to 'NODE-A' do not have the same node-name pairs (since the order is reversed), and can therefore be used as two distinct reference branches.

Rule 4: The numerical values for [R] and [L] are in the following units. Recall that variables XOPT and COPT come from the floating-point miscellaneous data card (see Section 1.0h) .

a) Specify R_{ij} in ohms

b) Specify inductances L_{ij} as

i) inductance L in mH if XOPT = 0 .

ii) reactance ωL in ohms at frequency $\frac{\omega}{2\pi} = \text{XOPT}$ if XOPT $\neq 0$.

Rule 5: Matrices [R] and [L] are symmetric, so only need be specified on and below the diagonal. The following format applies:

51	Nod names f 1st branch		R_{11}	L_{11}				
52	Node names of 2nd branch		R_{21}	L_{21}	R_{22}	L_{22}		
53	Node names of 3rd branch		R_{31}	L_{31}	R_{32}	L_{32}	R_{33}	L_{33}
54	Node names of 4th branch		R_{41}	L_{41}	R_{42}	L_{42}	R_{43}	L_{43}
			R_{44}	L_{44}				
55	Nod names of 5th branch		R_{51}	L_{51}	R_{52}	L_{52}	R_{53}	L_{53}
			R_{54}	L_{54}	R_{55}	L_{55}		

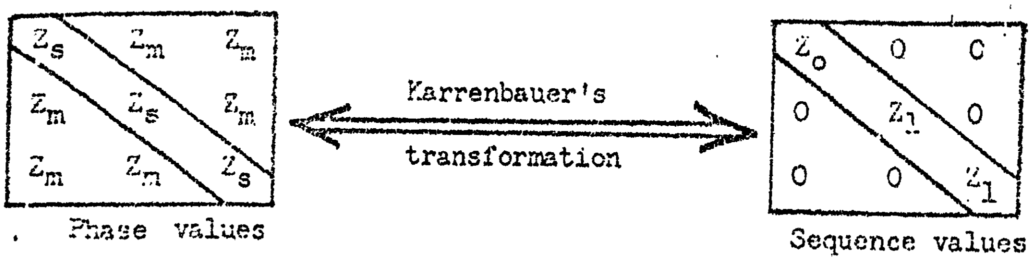
Etc.

When one card is not sufficient for all required R-L values (for the fourth and later elements), then "continuation" cards are used, with columns 1-26 left blank, it will be noted.

Rule 6: No branch current output is possible for this branch type. However, the branch voltage can be obtained on the first two phases (where column 80 of the card is not being used) by punching a "2" in column 80.

Optional use of Z_0 and Z_1 for 3-phase coupled R-L branches

Suppose that the user has exactly three coupled R-L branches, with the associated [R] and [L] matrices having common diagonal values Z_s and common off-diagonal values Z_m, as shown in the sketch. Then rather than inputting [R] and [L], it may be more convenient to input the associated zero and positive-sequence values, (R_0, L_0) and (R_1, L_1), respectively.



Phase values

Sequence values

Section 4.1 details the tranformation formulas of Karrenbauer which are assumed to apply, and the preceding format specification is modified slightly, giving the following:

ITYPE (1-2)	Node Names (3-8)	(9-14)	(15-26)	Sequence Values (27-32)	(33-44)
	BUS1	BUS2		R	L
I2	A6	A6		E6.2	E12.2

Rule A: Number the 3 phases 51, 52, and 53. Make out a branch card for each, in this sequence. Indicate this sequence by punching 51, 52, and 53 in columns 1-2 of these cards (field ITYPE).

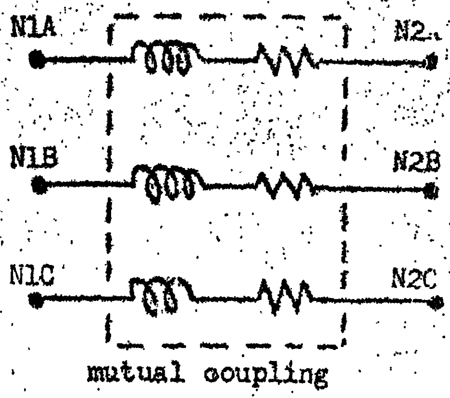
Rule B: Specify the phases by means of the names of the nodes at both ends (use columns 3-14; field names BUS1 and BUS2). Nodes may be grounded (indicated by blank field name) if desired.

Rule C: Resistance and inductance values are punched in columns 27-44 (fields R and L). Zero sequence values R_0, L_0 go on the first (phase 51) card, while positive-sequence values R_1, L_1 go on the second card; columns 15-80 of the third card are to be left blank. Units for R are ohms, while L is in mH unless XOPT ≠ 0 (in which case L is in ohms at frequency XOPT; see Rule 4).

Rule D: Once a 3-phase branch has been so inputted, it can be used as a reference branch for identical 3-phase branches to follow. See Rule 3 above.

> **WARNING!** If columns 15-80 of that third branch card are not left blank, the EMTP will not recognize the coupled branches as being specified with sequence values. In that case, the phase-domain format will be assumed, with the result being one very unbalanced, erroneous representation. Something as innocent as an illegal column-80 punch for branch current will cause big trouble (ask Al Legate; 7 April 1980).

Example: For the bus names as specified in the sketch, and sequence parameters as tabulated below, the associated input data cards should be as shown on the data form further below.



R_0 = 4.5 ohm R_1 = 3.1 ohm

L_0 = 87.6 mH L_1 = 66.4 mH

51	N1A	N2A		4.5	87.6
52	N1B	N2B		3.1	66.4
53	N1C	N2C			

Terminal node names of transformer

When using the impedance matrix program of Section 7.1 to generate [R] and [L], care must be exercised in naming the nodes of the windings. The printed output of [R] and [L] in Section 7.1 has rows and columns identified by the names "HIGH", "LOW", and "MEDIUM" (the last is only used when a 3-winding transformer is considered). Unless rows and columns of this result are to be permuted, node names BUS1 and BUS2 on the branch cards for the transformer (columns 3-14) must correspond to this order.

" .... AND IF YOU DON'T KNOW WHY, YOU AIN'T GOT
NO BUSINESS RUNNIN' THE PROGRAM NO HOW."

Alternate performance equations

The use of [A] and [B] instead of [R] and [L] is exactly as described for multiconductor Pi-circuits (see end of Section 1.23). This option is particularly useful for representing transformers which draw no magnetizing current; in this case, [R] and [L] do not exist, though [A] and [B] do. For marginal cases of very-high magnetizing impedance, one avoids the near-singularity problem, with its associated need for high precision on input data.

The saturable transformer component of Section 1.25 is based on this approach, with N-1 2x2 matrices (A) and (B) used to represent the N-1 ideal transformers and associated non-primary leakage impedances. In this case, (A) and (B) are symmetric, so there is no problem. But the general case of 3x3 matrices (R) and (L) can not be converted to (A) and (B) representation, since (A) and (B) will then not be symmetric. See Ref. 22, issue 2, page 14.

1.25 Saturable Transformer Components

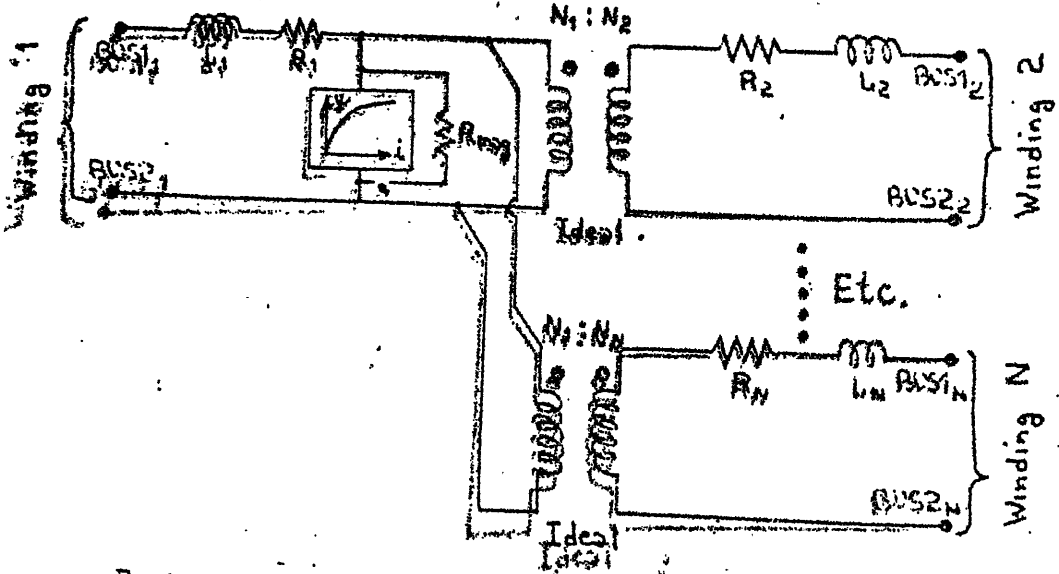
Single-phase transformer

The single-phase N-winding transformer shall be considered first. It is a building block for the 3-phase 3-leg core-type unit to be considered later.

Actually, the use of saturation is not mandatory. If the flux-current magnetization characteristic consists of a single finite-slope segment, then all-linear components are used in the model, and numerically the resulting solution will be identical (except for roundoff differences) to that of Section 1.24 where matrices [R] and [L] are used. Thus even in the linear case, the present section may be used; it may be found to be more convenient and more general than Section 1.24 .

The saturable N-winding single-phase transformer in question is modelled as per the figure below. Pertinent points include the following:

1. N-1 single-phase, 2-winding ideal transformers are involved, providing the correct transformation ratios of windings 2, 3, ... , N with respect to winding 1 .
2. Each winding k has an associated leakage-impedance branch, characterized by resistance R_k and inductance L_k . All leakage inductances with the exception of L_1 must be nonzero.
3. Saturation and magnetizing-current effects are confined to a single nonlinear reactor in the winding-1 circuit. This is internally modelled as a type-98 pseudo-nonlinear reactor, should the saturation characteristic have two or more segments; for a single segment, a simple, constant linear inductance element is used ---- in which case the transformer is completely linear.
4. Core losses are confined to the constant, linear resistance R_{mag} which is in parallel with the saturation branch.



Equivalent circuit used to represent saturable, N-winding, single-phase transformer.

To input such a single-phase saturable transformer component, the following rules apply:

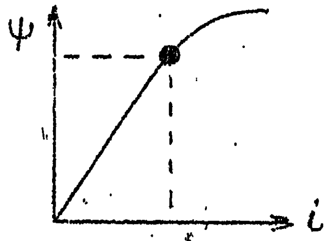
Rule 1: The first data card for the component is to be punched according to the following format:

1	2	3 4 5 6 7 8 9 10 11 12 13 14	15 16 17 18 19 20	21 22 23 24 25 26	27 28 29 30 31 32	33 34 35 36 37 38	39 40 41 42 43 44	45 46 47 48 49 50		80
		Special request word	Refer. name BUS3		i_{steady}	Ψ_{steady}	BUSTOP	R_{mag}	• • •	IOUTMG
		TRANSFORMER	A6		E6.2	E6.2	A6	E6.2		I1

"Special-request-word" field is punched with the 10 characters "TRANSFORMER ".

BUS3 ------- Reference-component name. Leave blank unless using the reference-component procedure of Rule 4.

i_{steady}, Ψ_{steady} --- Components of point in the flux-current plane used to define the linear inductance which represents the magnetizing branch during the phasor steady-state solution. Meaning is as in Section 1.33.



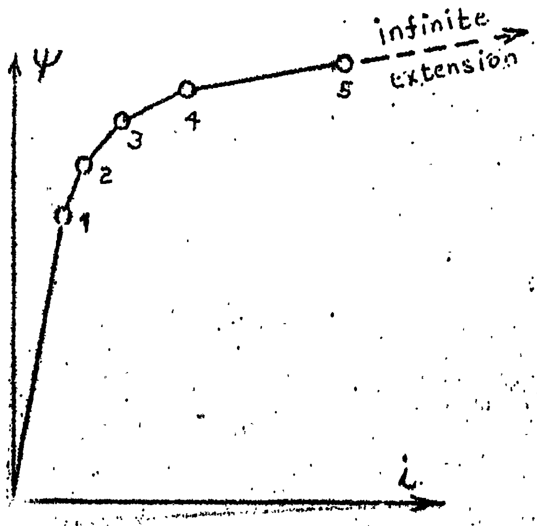
BUSTOP ------ A 6-character alphanumeric name for the internal bus at the top of the magnetizing branch. This name uniquely identifies the transformer.

IOUTMG ----- Output specification for magnetizing-reactance branch. Punch "1" for branch current, "2" for branch voltage, or "3" for both.

R_{mag} ------- The constant, linear resistance which parallels the magnetizing reactance, accounting for core loss. The specification is in ohms, with a value of zero or blank taken to mean $R_{mag} = \infty$.

Rule 2: Assuming that the reference name BUS3 is left blank, the card of rule 1 is followed by cards which define the saturation characteristic of the magnetizing branch. Format is exactly like for the type-98 pseudo-nonlinear reactor of Section 1.29.

a) The origin ($i=0$, $\Psi=0$) is an implied point, not to be input explicitely.



b) Current and flux pairs for the breakpoints are punched in fields CUR and FLUX . These use columns 1-32, one pair of values per card, inputted in monotone-increasing order (movement away from the origin). Both coordinates must be strictly monotone increasing.

CUR	FLUX
E16.0	E16.0

c) The final point on the characteristic merely defines the slope of the final segment, which is assumed to extend to infinity. The last point is followed by a terminating card with "9999" punched in columns 13-16.

	9999

Normally the first point of the characteristic will equal $(i_{steady}, \psi_{steady})$ in order to provide continuity between steady-state and transient solutions at time zero, though this is not mandatory. Note that if only one i-ψ point is inputted, a linear transformer results; with no i-ψ data points preceding the 9999-card, the magnetizing reactance is assumed not to exist.

Rule 3: For each transformer winding k (k=1, 2, ... , N), the user inputs a winding card in the following format:

ITYPE	Node names			Leakage Z		Volts		IOUT
	BUS1	BUS2		R_k	L_k	(N_k)		
I2	A6	A6		E6.2	E6.2	E6.2		I1

Identifying node names for the current output will be "BUS1" of the primary terminals, and internal node "BUSTOP"

ITYPE ----- Winding number (1, 2, ...). Cards must be placed in natural order, with winding 1 first, then winding 2, etc.

BUS1, BUS2 ----- Six-character node names of the busses to which the winding in question is connected. As usual, a blank field is taken to mean ground.

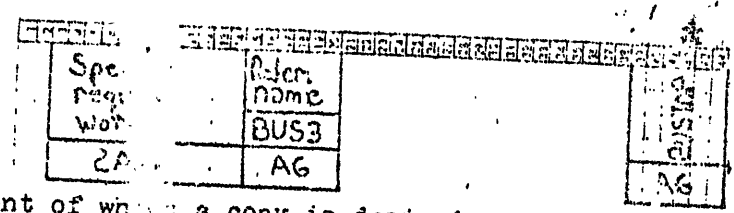
R_k, L_k ----- Leakage values associated with the winding in question. R_k is resistance in ohms, while L_k is inductance in mH (unless XOPT parameter of 1st misc. data card is nonzero, in which case L_k is in ohms at frequency XOPT Hz). R_k may be zero, but L_k must be nonzero (with the exception of winding 1, where $L_1 = 0$ is permitted if $R_1 \neq 0$).

Volts ----- A number proportional to the number of turns of the winding in question. It is convenient simply to use the rated winding voltage in kV.

IOUT ----- Only for winding 1 (the primary), a 1-punch in column 80 will make branch current i_1 an output variable.

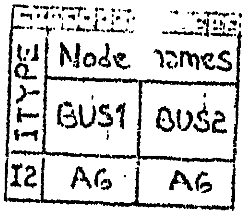
Rule 4: Should the user desire to specify a transformer having parameters identical to those of a previously-inp[illegible]d unit, he can use the following reference-component procedure:

a) On the card of rule 1, punch only the fields shown at the right. Field BUS3 now carries the name which was punched as variable BUSTOP (cols. 39-44) for the reference component of which a copy is desired.



b) Omit the cards of Rule 2 (the i- ψ curve).

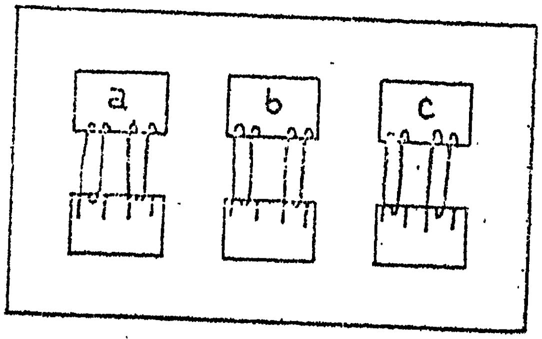
c) For the cards of Rule 3 (the winding cards), punch only the fields shown at the right.



The user is encouraged to use this option whenever possible, as it saves storage space in certain program tables, and avoids possible numerical error in the data associated with the components which are copied.

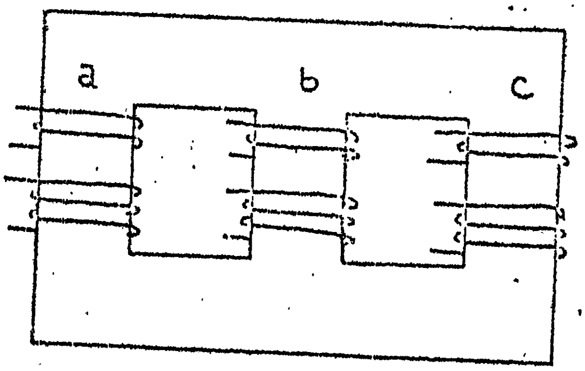
Three-Phase Transformer

In a 3-phase shell-type transformer, an iron-core path is provided for the return of zero-sequence flux. For this case, it is reasonable to model the device with 3 separate single-phase units, thereby assuming that the magnetic induction of the three phases is independent. In this way, a 3-phase shell-type transformer presents no complication.



3-phase shell-type transformer

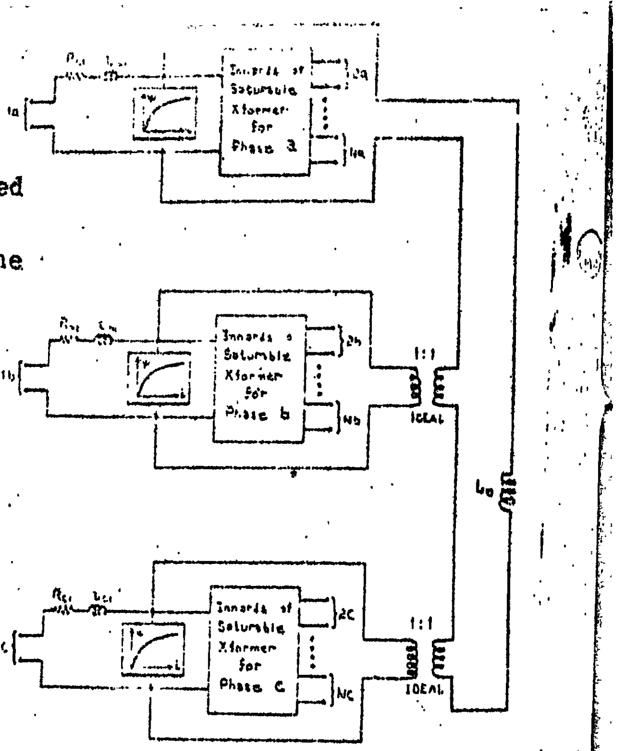
But for the 3-phase, 3-leg, core-type transformer, zero sequence flux is forced to return through the air. As the resulting performance is radically different (in general; for situations where the zero-sequence is excited) than that of three single-phase units, a new 3-phase component is clearly called for. Such a component now exists in the T.P., conforming to the following assumptions:



3-phase, 3-leg, core-type transformer

Assumption a)

A magnetization characteristic i- ψ is known for each of the three legs of the transformer. For any one leg (any phase), this characteristic relates the flux in the leg to the MMF difference between the two ends of the leg (top and bottom in the sketch). Note that this is not the experimentally-measured curve obtained from one winding of one phase, with all others open-circuited.

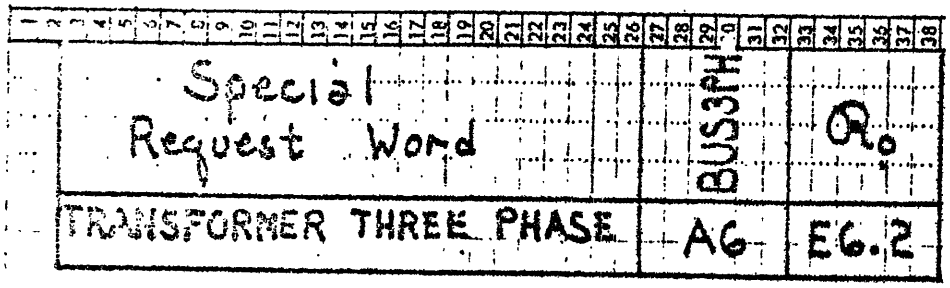

Innards of Saturable Xformer for Phase a
Innards of Saturable Xformer for Phase b
Innards of Saturable Xformer for Phase c
1:1
IDEAL
1:1
IDEAL
L_0

Assumption b)

The air-return path for zero-sequence flux is assumed to have known, constant magnetic reluctance $\mathcal{R}_o$. By definition, zero-sequence flux travels between the top and bottom members of the unit, through the air.

With this physical data available, a 3-phase core-type transformer can be modelled as in the figure at the right. Note that this is an interconnection of three saturable single-phase transformers, two ideal isolation transformers, and a zero-sequence inductance L_o . Data input for this model i according to the following rules:

Rule 5: Begin with a request card for the 3-phase transformer component, using the following format:



1–26	27–32	33–38
Special Request Word	BUS3PH	$\mathcal{R}_o$
TRANSFORMER THREE PHASE	A6	E6.2

The field marked "Special Request Word" (columns 3-26) is to be punched with the 24 characters "TRANSFORMER THREE PHASE " .

BUS3PH ----- A 6-character alphanumeric name associated with the transformer. This should be distinct from all other names used in the study.

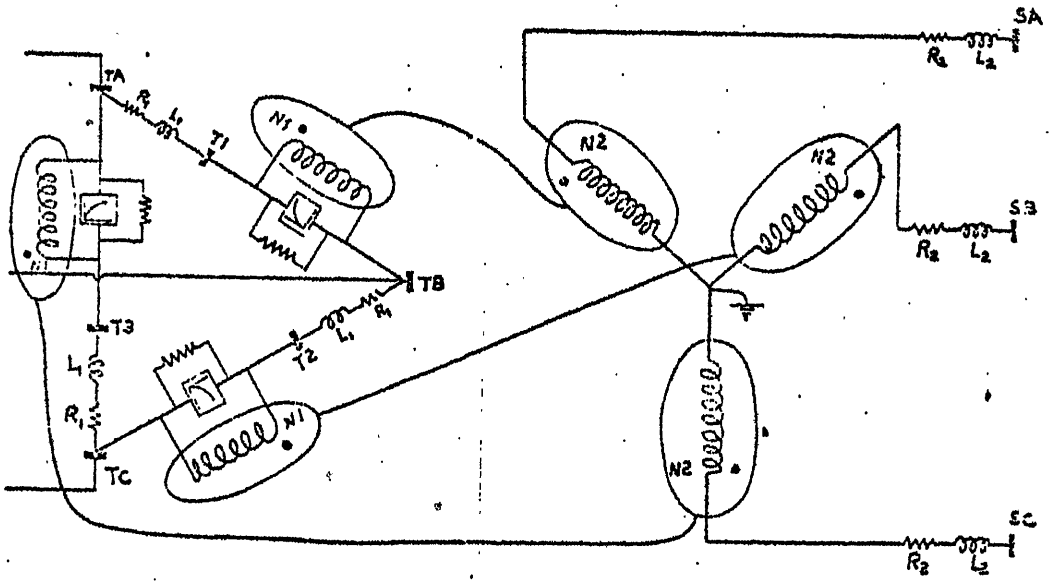
$\mathcal{R}_o$ -------- Reluctance of the zero-sequence air-return path for flux. In the circuit, $L_o = N_1^2/\mathcal{R}_o$. Units used should be consistent with current and voltage used elsewhere; the units for "time" are always seconds.

Rule 6: The preceding request card is to be followed by data cards for three saturable, single-phase transformer components. These single-phase transformers have parameters which would exist if a perfect magnetic short circuit (i.e., a magnetic connection with a member having infinite permeability) were placed between the top and the bottom ends of the cores. The reference-component procedure (Rule 4) can be used for any and/or all of the single-phase units in question. In order of input, this transformer data defines the 3 saturable single-phase units of the above equivalent circuit. As the 2 ideal transformers and their associated interconnection is handled automatically by the program, this completes the data input for the 3-phase, 3-leg, core-type unit.

Delta transformer connections

Delta transformer connections can sometimes be a little tricky. They also are not uncommon, so that a little specific explanation of this configuration is perhaps in order.

First, there is the equivalent circuit when modeled using three single-phase saturable transformer components. If it is the primary which is delta connected, and if the secondary is grounded-Wye, then the following sketch shows the resulting interconnection of elementary components:

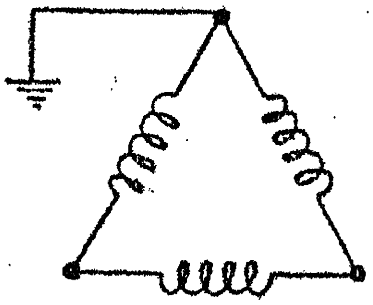


Here R_1 and L_1 are the primary leakage-impedance parameters (assumed to be the same for all three transformers), and R_2 and L_2 are those for the secondary. Bus "T1" is the internal node "BUSTOP" for the first single-phase transformer whose primary terminals are "TA" and "TB", and whose secondary terminals are "SA" and ground. Et cetera for the other two single-phase transformers, as per the following EMTP data-setup listing (for details, see Ref..8, November 12, 1975):

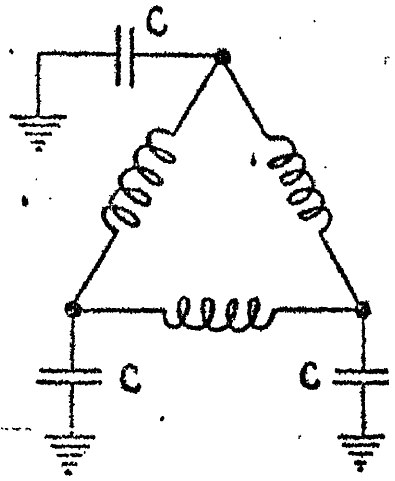
```
  TRANSFORMER             2.0   1137. T1    3.00E5
 2.              1137.
 50.             1365.
10000.           1478.6
            9999
 1TA    TB                 .25   25.  3.03E5
 2SA                       .25   25.  3.03E5
  TRANSFORMER T1                      T2
 1TB    TC
 2SB
  TRANSFORMER T1                      T3
 1TC    TA
 2SC
```

A second principal point concerns the need for a path to ground on the delta side of the bank; a floating delta is not allowed, since mathematically the voltages there would then only be defined within an arbitrary constant. Of course if a transmission line is connected to the delta side, there is no problem, since line capacitance provides the connection to ground. Likewise a connection to one or more voltage sources, either direct or through other "simple" elements, will satisfy the requirement. But the common, isolated, delta-connected tertiary of 3-winding transformers requires special attention. There are two common, general approaches:

Unbalanced solution : If the user is interested not at all in voltages on the delta side, it is convenient to simply ground one corner of the delta (see sketch). This provides the needed ground connection without altering the problem solution elsewhere (since no current can flow in the connection to ground anyway, by Kirchhoff's current law).



Balanced solution : If preserving the inherent balance on the delta side is important, then stray capacitance can be added. The simplest procedure is to connect three equal capacitors from the corners of the delta to ground, as in the sketch at the right. Caution must be exercised to use realistic values, however; as such capacitors go to zero, a matrix singularity will be approached, and the user will get into trouble with miscellaneous data parameter singularity tolerances "EPSILN" and "TOLMAT" (see Section 1.0h explanation). The EMTP memorandum of November 12, 1975 (Ref. 8), Fig. 2 shows a value of 0.003 μF being used on each corner of the delta connection of a 25-kV delta to 500-kV Wye transformer bank.



Warning About Possible 3-Winding Numerical Instability

A warning about possible numerical instability must be given, with respect to the three-winding saturable "TRANSFORMER" component. As of August 1977, three different groups of EMTP users have observed the problem:

1. Dick Webster of Pacific Gas & Electric in San Francisco, California;
2. Alan Courts of BPA, Portland, Oregon;
3. An associate of Dr. Brian Dixon of B.C. Hydro, Vancouver, B.C.

The obvious symptom of trouble with such numerical instability will be a string of Message-18 printout ("TROUBLE AT 73912 ON TYPE-99 OR 98 ELEM NUMBER .....") as described in Section 2.2h . This assumes that the magnetization characteristic is truly nonlinear (two or more sections), so will be internally represented by a Type-98 pseudo-nonlinear inductance element.

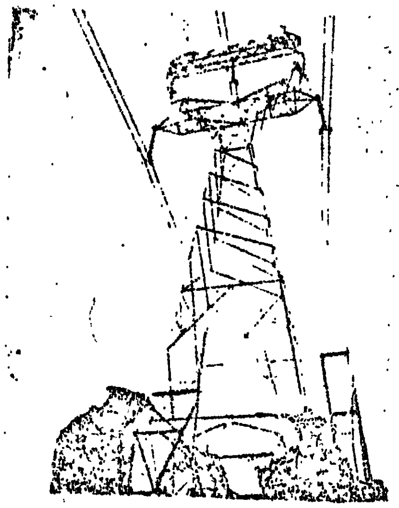
The Message 18 printout is somewhat deceptive, in that there really is no trouble with the Type-98 element at all. If one looks at network node voltages. he will see in such cases that the solution is diverging; it is blowing up exponentially. Program Maintenance at BPA looked at Dick Webster's problem in some detail. The transient simulation was really just a continuation of the 60 Hz steady state phasor solution; and for two or three cycles, the graphs appeared to the eye to be perfectly sinusoidal. There was no abrupt discontinuity or shock at any point. Rather, it appeared simply that roundoff error (numerical noise) was being amplified as the simulation progressed; one could not detect exactly when the "hash" began, but it appeared to grow exponentially with time. Physically, the performance was what an engineer might expect had there been negative damping in the system. Dick's case, which still looked nice and sinusoidal at 50 msec , was blown off the machine with exponent overflow by about 100 msec, as I recall.

So what is the reason for such erroneous behavior? It is not believed to be an EMTP bug (programming error). Hermann (Prof. Dommel) has some ideas, but we are not prepared to formally state anything at this time. The user should be aware of the potential for trouble in the 3-winding case, however. Yet he is not necessarily advised to avoid all 3-winding saturable "TRANSFORMER" usage, since most situations seem to pose no trouble. An example of trouble-free usage will be found in the CPU Stolle Road problem of UTPF Test Case #17.

The "XFORMER" supporting routine of Section 7.1 does provide an alternative to the use of the saturable "TRANSFORMER" component. The resulting transformer representation will be linear, however. Also, not over three windings are allowed at present. Here the approach is to generate [R] and [L] matrices, to be used as per Section 1.24 .

1.26 Branch Cards for Distributed-Parameter Transmission Lines

General Comments

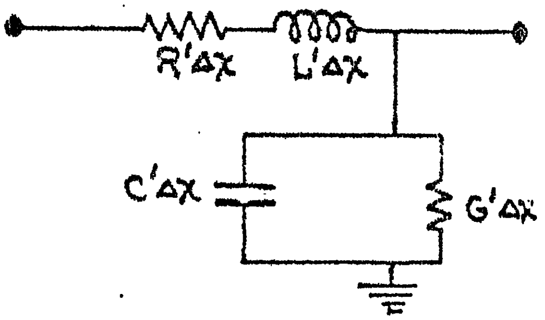


The modelling used to represent transmission lines in the Transients Program poses a number of possibilities for the user.

To start the analysis, one can write the "exact" partial differential equations governing the voltage and current on the line. For N phases (conductors), these are

$$-\frac{\partial \vec{v}}{\partial x} = [L]\frac{\partial \vec{i}}{\partial t} + [R]\vec{i}$$

$$-\frac{\partial \vec{i}}{\partial x} = [C]\frac{\partial \vec{v}}{\partial t} + [G]\vec{v}$$



Incremental section, length = Δx

Although the incremental section of line has been sketched only for N = 1, in general these are vector-matrix equations, where [L], [R], and [C] can be determined from a line-constants program. See "LINE CONSTANTS" of Sect. 7.4.

"S" ⇒ Self

"M" ⇒ Mutual

S	M	M
M	S	M
M	M	S

Now if the transmission line is assumed to be transposed (or just balanced, if 2-phase), then all matrices have only two distinct element values: all diagonals have a common value "S", and all off-diagonals have a common value "M". Only under this assumption can the line be represented as truly distributed in the Transients Program at the present time. If such a transposition assumption is not realistic for the study being contemplated, the user can cascade lumped-parameter Pi-sections, each of which approximately represents the actual construction over the maybe 20 or so miles of the section. Yet such a lumped-parameter solution is costly in computer time and storage requirements, so should be avoided if practical.

Assuming distributed representation, the transposition assumption allows for modal decoupling by means of Karrenbauer's transformation (see Section 4.1). The N mutually-coupled equations in phase (regular; original) variables are converted into N equivalent uncoupled single-phase problems ---- a zero-sequence (ground) mode and (N-1) identical positive-sequence (line) modes.

$$\begin{bmatrix} R_s & R_m & \cdots & R_m \\ R_m & R_s & \cdots & R_m \\ \vdots & \vdots & \ddots & \vdots \\ R_m & R_m & \cdots & R_s \end{bmatrix} \xrightarrow{\text{Diagonalization}} \begin{bmatrix} R_G & & & 0 \\ & R_L & & \\ & & \ddots & \\ 0 & & & R_L \end{bmatrix}$$

Phase domain

Modal domain

"G" ⇒ Ground mode

"L" ⇒ Line mode

where

$$R_s = \{R_G + (N-1)R_L\} / N \qquad R_G = R_s + (N-1)R_m$$

$$R_m = \{R_G - R_L\} / N \qquad R_L = R_s - R_m$$

Line resistance R, inductance L, and capacitance C are inputted on this basis: one set of values for the zero sequence, and a second set for the $(N-1)$ positive sequences.

As a single-phase transmission line is mathematically identical with its zero sequence (i.e., transformation produces no change), this special case simply has no positive-sequence values; only zero sequence data is inputted.

Distortionless line modelling

A transmission-line mode is well known[6] to be distortionless if parameters for that mode satisfy the relation $R/L = G/C$. Of course actual leakage conductance for an overhead line is very nearly zero, and no provision for inputting a nonzero value is provided by this program anyway. If the user wants distortionless-line modelling, it is presumed that the input value of R' is meant to be a measure of the total line losses. Therefore the program splits the losses into series and shunt losses by computing the series resistance R'_{series} and the leakage conductance G'_{leak} from the relation

$$\frac{R'_{series}}{L'} = \frac{G'_{leak}}{C'} = 0.5\left(\frac{R'}{L'}\right)$$

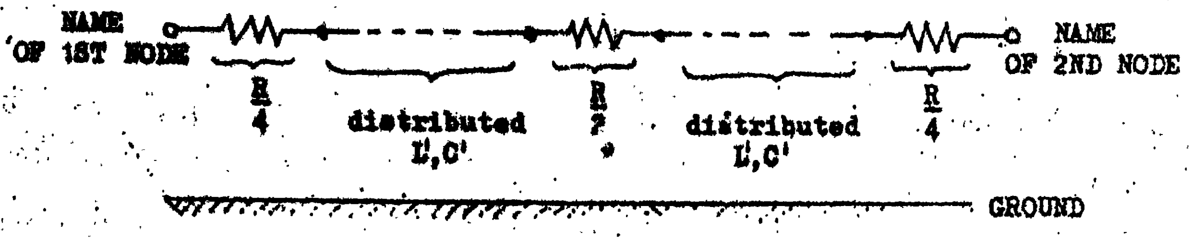
With this formula, the ac steady-state results are practically identical whether the line is modelled as distortionless or in the other two ways to follow. Transient responses differ mainly in the initial rise of voltage pulses. The attenuation constant α is found from the relation

$$\alpha = \frac{1}{2} \cdot \frac{R'}{L'} \cdot \sqrt{L'C'} = \frac{1}{2} \frac{R'}{Z} \text{, with } Z = \sqrt{\frac{L'}{C'}} .$$

The corresponding decrement factor is $e^{-\alpha \ell}$, where ℓ is the line length. Such distortionless modelling is generally used only for the positive sequence, if at all.

Lumped-resistance line modelling

The second (and only other) distributed model which is readily solvable is that in which the series resistance is pulled outside of the distributed line, and represented as a lumped element. This is the most common representation used in BPA studies, the standard representation which is assumed unless the user specifically requests otherwise (see variable IPUNCH, cols. 53-54). The program automatically cuts the line in two, inserting half of the resistance in the middle, and one fourth at each end:



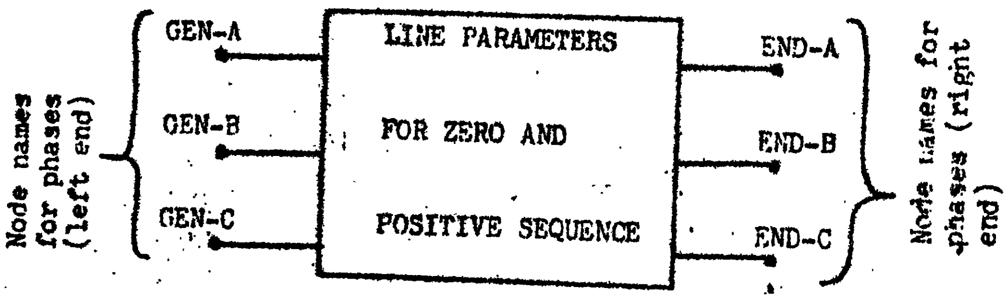
The half-length distributed sections then become lossless (hence distortionless, with attenuation $\alpha = 0$). Both modes of most lines in BPA studies are usually so represented at present. See further comments in Section 4.2 .

Frequency-dependent modelling

The resistance and inductance of the zero-sequence mode are typically quite variable with frequency; the resistance in particular, which is furthermore substantially larger than for the positive-sequence mode. "Exact" distributed-parameter representation is now available for the zero sequence, as described in Section 1.26b .

Data format for distributed-parameter line cards

To specify an N-conductor, transposed, distributed-parameter transmission line, conform to the following rules and format:



Rule 1: Number the phases -1, -2, -3, ... , -N . Make out one branch card for each phase, and stack them in this sequence. Indicate this sequence by punching -1, ... -N in columns 1-2 of these cards (field ITYPE). N cannot exceed 9 phases.

Rule 2: Specify each of the phases -1, ... , -N by the names of the nodes at both ends (columns 3-14; field names BUS1, BUS2). Nodes may be grounded (indicated by blank name field) if desired.

Rule 3: If the parameters for this line are identical to those of another N-phase line previously inputted, then the option of rule 4 in section 1.23 may be used, except that no storage is saved here. Columns 15-26 with field names BUS3 and BUS4 are used in this case. Otherwise, they are left blank.

Rule 4: Specify the zero-sequence parameters on the first card (the card for the first phase), and the positive-sequence parameters on the second card (the card for the second phase). The four basic pieces of information needed are resistance, inductance, capacitance, and length; yet three forms for this input are possible:

a) In all cases, punch resistance R' in ohms per unit length in columns 27-32, and line length ℓ in consistent units in columns 45-50.

b) Parameter ILINE (columns 51-52) determines how L' and C' may be disguised. Remember that variables XOPT and COPT come from the floating-point (first) miscellaneous data card of Section 1.0h .

ILINE	"A" ---- columns 33-38	"B" ---- columns 39-44
0	L' in mH/length if XOPT = 0 Reactance $\omega L'$ in Ω/length at frequency XOPT if XOPT $\neq$ 0	C' in μF/length if COPT = 0 Susceptance $\omega C'$ in μmho/length at frequency COPT if COPT $\neq$ 0.
1	Surge impedance Z_s in ohms $Z_s = \sqrt{L'/C'}$	Propagation velocity in length/sec $v = 1/\sqrt{L'C'}$
2	Surge impedance Z_s in ohms $Z_s = \sqrt{L'/C'}$	Travel time τ of line, in sec $\tau = \ell / v = \sqrt{L'C'}\,\ell$

Rule 5: Output options for printing and/or plotting use a column-80 punch (variable IOUT). Only for a single-phase line is branch-current output possible. Within this restriction though,

$$\text{IOUT} = \begin{cases} 1 \Rightarrow \text{branch current output only} \\ 2 \Rightarrow \text{branch voltage output only} \\ 3 \Rightarrow \text{both branch current and voltage output} \end{cases}$$

A blank or zero will give you no such output, of course.

Rule 6: Both modes of a line must have travel time τ in excess of the time step size Δt (Sect. 1.0h). If not, the program will stop with an error message (see Section 2.4).

Rule 7: Both L' and C' must be nonzero for each mode.

Rule 8: Variable IPUNCH of columns 53-54 specifies the type of modelling to be used on the mode of the card in question:

$$\text{IPUNCH} = \begin{cases} 0 \Rightarrow \text{lumped-resistive modelling (the usual case)} \\ 1 \Rightarrow \text{distortionless-mode modelling} \\ -1 \Rightarrow \text{frequency-dependent mode modelling (for zero seq. only);} \\ \qquad \text{refer to Sec. 1.26b for extra data cards required.} \end{cases}$$

It is not obligatory to model the two modes of a multi-phase line the same way.

3-8	9-14	15-20	21-26	27-32	33-38	39-44	45-50	51-52	53-54		80
Node Names		Reference br.		Resistance R' [Ω/length]	A	B	Line length ℓ	ILINE	IPUNCH		IOUT
BUS1	BUS2	BUS3	BUS4								
A6	A6	A6	A6	E6.2	E6.2	E6.2	E6.2	I2	I2		I1

Example: Consider the 3-phase line shown in the sketch above the preceding format rules. Suppose that line length is 180 miles, with parameters as follows:

	R' [ohm/mile]	L' [H/mile]	C' [μFd/mile]
Zero seq.	10.9	.0774	.0107
Pos. seq.	.0484	.0294	.0192

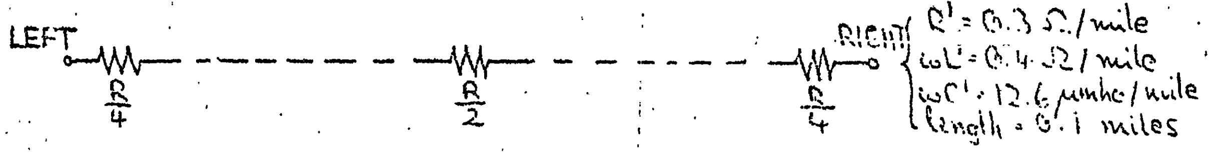
Corresponding data cards for input to the Transients Program then are:

```
12345678901234567890123456789012345678901234567890123454
-1 GEN-A END-A              10.9    77.4 .0107 180.
-2 GEN-B END-B             .0484    29.4 .0192 180.
-3 GEN-C END-C
```

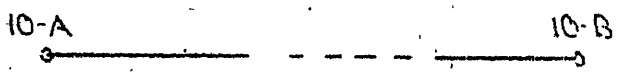
Example: Consider four separate, uncoupled single-phase lines, as per the sketches below. Corresponding input cards might then be as follows:

```
-1 LEFT  RIGHT              0.3    0.4   12.6   0.1  0
-1 10-A  10-B                     260.    .66        2
-1   PT    XY               0.2   300.  3.0E5  200.  1
-1   L1    R1  LEFT  RIGHT
```

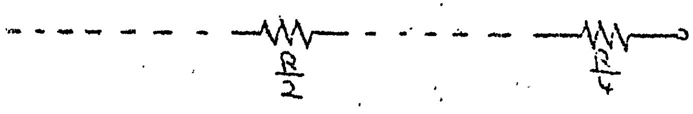
(assuming XOPT=60 and COPT=60 ; see floating-point miscellaneous data parameters, Section 1.0h):



$R' = 0.3\ \Omega/\text{mile}$
$\omega L' = 0.4\ \Omega/\text{mile}$
$\omega C' = 12.6\ \mu\text{mho/mile}$
length = 0.1 miles



$R' = 0.$
$Z_s = 260\ \Omega$
$\tau = 660\ \mu s$



$R' = 0.2\ \Omega/m$
$Z_s = 300\ \Omega$
$v = 300 \cdot 10^6\ m/s$
length = 200 m

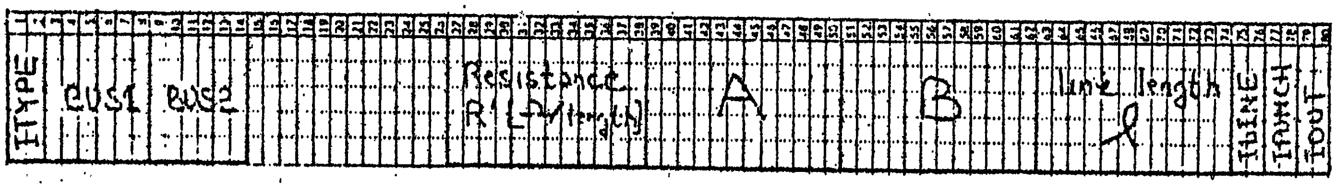
Alternate high-precision format

The $VINTAGE card (see Section 1.-D), which is honored by most computer systems, provides for an alternate high-precision format. Specifically, the R,A,B,L fields can be switched to 4E12.0 (columns 27-74 in this case) if $VINTAGE, 1 precedes such a group of new branch cards, and $VINTAGE, 0 follows the grouping. As of August 1980, Pi-circuits (Section 1.23) and the simple series R-L-C branch (Section 1.21) are other components which allow such new, wider formats; they can also be included in the grouping between the $VINTAGE cards, then:

$VINTAGE, 1

Any mixture of series R-L-C, Pi-circuit, and distributed line cards, as long as all use the new wide formats.

$VINTAGE, 0



1.26a SPECIAL DOUBLE-CIRCUIT DISTRIBUTED LINE, WITH ZERO-SEQUENCE COUPLING

General Applicability

The double-circuit configuration, where both circuits share the same right of way, is common enough so as to deserve special attention. Here the restriction to two 3-conductor circuits is made, for a total of six phases or conductors for the component. The modeling option of this section assumes that the circuits are themselves individually continuously transposed, but that there is inter-circuit zero-sequence coupling. As such, it is a special 6-conductor extension to the continuously-transposed distributed-parameter transmission line modeling of Section 1.26 .

$$\begin{bmatrix} \boxed{Z_s} & Z_m & Z_m & Z_m & Z_m & Z_m \\ Z_m & \boxed{Z_s} & Z_m & Z_m & Z_m & Z_m \\ Z_m & Z_m & \boxed{Z_s} & Z_m & Z_m & Z_m \\ Z_m & Z_m & Z_m & \boxed{Z_s} & Z_m & Z_m \\ Z_m & Z_m & Z_m & Z_m & \boxed{Z_s} & Z_m \\ Z_m & Z_m & Z_m & Z_m & Z_m & \boxed{Z_s} \end{bmatrix}$$

Fig. 1. Matrix structure assuming continuous transposition.

$$\left[\begin{array}{ccc|ccc} \boxed{Z_s} & Z_m & Z_m & Z_p & Z_p & Z_p \\ Z_m & \boxed{Z_s} & Z_m & Z_p & Z_p & Z_p \\ Z_m & Z_m & \boxed{Z_s} & Z_p & Z_p & Z_p \\ \hline Z_p & Z_p & Z_p & \boxed{Z_s} & Z_m & Z_m \\ Z_p & Z_p & Z_p & Z_m & \boxed{Z_s} & Z_m \\ Z_p & Z_p & Z_p & Z_m & Z_m & \boxed{Z_s} \end{array}\right]$$

Fig. 2. Structure of matrices for new double-circuit line having zero-sequence coupling between circuits.

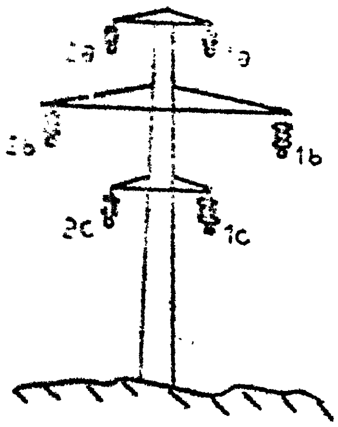


Fig. 3. Double-circuit line supported by a single tower.

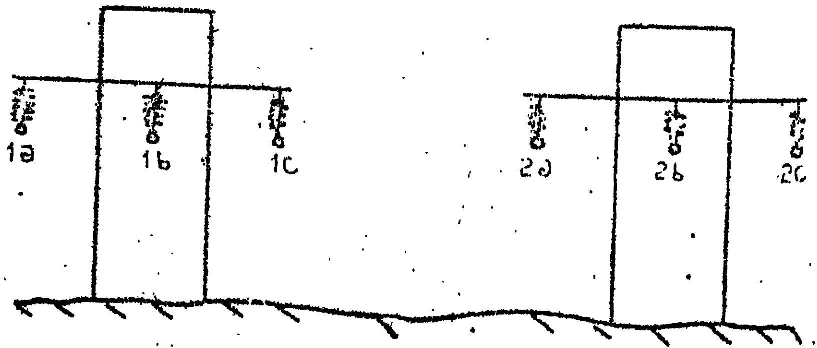


Fig. 4. Double-circuit line where each circuit is supported by its own towers.

163

In general terms, the special double-circuit representation of this section is to be preferred if the two circuits are physically separated, as in Fig. 4; if both circuits are supported by the same tower as in Fig. 3, there is questionable if any advantage over the conventional continuously-transposed representation of Section 1.26 .

Mathematics of Double-Circuit Model

Mathematically, the coupling (resistive, inductive, and capacitive; we use the general symbol "Z" simply for illustration) between phases is assumed to have the structure of Fig. 2, where three distinct parameters are seen to be allowed. This is to be contrasted with the continuously-transposed model of Fig. 1, where there are only two distinct parameter values. Several specific points concerning this difference follow:

Point 1: The two circuits of the double-circuit component representation are assumed to be identical. That is, rows and columns 1, 2, and 3 of Fig. 2 can be interchanged (permuted) with those of 4, 5, and 6 without altering the matrix. In Fig. 5, the two 3 x 3 diagonal submatrices $[Z_{11}]$ and $[Z_{22}]$ are identical.

Point 2: Z_s and Z_m are the self and mutual coupling associated with either one circuit taken separately. With variable grouping after row and column 3 in Fig. 2, the partitioned matrix form or structure of Fig. 5 results. Note that $[Z_{11}]$ and $[Z_{22}]$ each are of the form of Section 1.26, which means mathematically that each circuit taken individually is continuously transposed.

$$\begin{array}{|c|c|}\hline Z_{11} & Z_{12} \\ \hline Z_{21} & Z_{22} \\ \hline \end{array}$$

Fig. 5. Partitioned form of matrix of Fig. 2 (each block is 3 x 3).

Point 3: All elements of $[Z_{12}]$ or $[Z_{21}]$ are equal to the same value Z_p ——— the mutual coupling between any one of the three conductors of one circuit & any one of the three conductors of the other circuit.

Point 4: The three distinct phase coupling parameters Z_s , Z_m , and Z_p can be indirectly specified by means of the three distinct modal coupling parameters Z_G , Z_L , and Z_{IL} . The relationship is:

$$Z_G = Z_s + 2Z_m + 3Z_p$$
$$Z_L = Z_s - Z_m$$
$$Z_{IL} = Z_s + 2Z_m - 3Z_p$$

Here Z_G is the ground-mode parameter, identical to the value for the zero-sequence mode of the continuously-transposed line of Section 1.26 if parameters Z_p and Z_m happen to be equal (so that the six conductors actually are continuously transposed). Parameter Z_L is identical with the familiar line-mode of the continuously-transposed line, always, and has modal multiplicity of four. Finally, parameter Z_{IL} is completely new, a line mode associated with intercircuit zero-sequence coupling.

Point 5: Further details can be found in Reference 7, plus the September 19, 1974 memorandum of Reference 8. Simply for easy reference, the modified-Karrenbauer diagonalizing transformation which is used for the double-circuit component is the following:

$$[S] = \frac{1}{6} \cdot \left[\begin{array}{ccc|ccc} 1 & 2 & 2 & 1 & 0 & 0 \\ 1 & -4 & 2 & 1 & 0 & 0 \\ 1 & 2 & -4 & 1 & 0 & 0 \\ \hline 1 & 0 & 0 & -1 & 2 & 2 \\ 1 & 0 & 0 & -1 & -4 & 2 \\ 1 & 0 & 0 & -1 & 2 & -4 \end{array}\right] \qquad [S]^{-1} = \left[\begin{array}{ccc|ccc} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 0 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 & 0 \\ \hline 1 & 1 & 1 & -1 & -1 & -1 \\ 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1 & 0 & -1 \end{array}\right]$$

Here we are using the notation $\vec{X}^{phase} = [S]\vec{X}^{mode}$, for any vector $\vec{X}$.

EMTP Data Format for Double-Circuit Distributed Line

Data preparation and input for the double-circuit distributed-parameter line component is the same as that for a continuously-transposed line (see Section 1.26) of six conductors, except for the following:

Comment 1: The three conductors of one of the circuits must be numbered -1, -2, and -3; conductors of the other circuit are then numbered -4, -5, and -6.

Comment 2: Modal parameter values are to be punched on the first three data cards (corresponding to conductors -1, -2, and -3) in the following order:

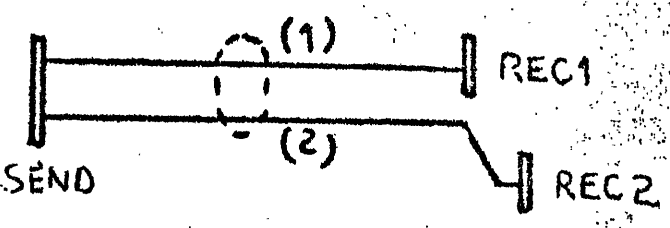
a) The "G" mode goes on the card of conductor 1, and the "L" mode goes on the card of conductor number 2. Note that for the special case of Z_p and Z_s being equal, this data input is absolutely identical to what would have been done for the continuously-transposed line model.

b) The "IL" mode goes on card number 3 (that for the third conductor).

c) Cards 4 through 6 are to be left blank, for columns 27-80.

The fields and units used for such data of columns 27-80 are identical to those for the continuously-transposed line, with frequency-dependent line constants (see Sect. 1.26b) allowed only for the "G" mode at present.

Exampl : Consider a 180-mile double-circuit line having the one-line diagram as sketched at the right. Note that termination of both lines is on the same 3-phase bus "SEND" at one end, while on different busses ("REC1" and "REC2") at the other end. Assumed sequence parameters for this line are taken to be:



	R [ohm/mile]	L [H/mile]	C [µFd/mile]
Mode G	0.58	0.00340	0.0091
Mode L	0.034	0.00068	0.0166
mode IL	0.035	0.00110	0.0116

Data cards for input to the T.P. then might appear as follows:

```
12345678901234567890123456789012345678901234567890123456
-1SENDA REC1A                .58   3.4  .0091  180.
-2SENDB REC1B               .034   .68  .0166  180.
-3SENDC REC1C               .035   1.1  .0116  180.
-4SENDA REC2A
-5SENDB REC2B
-6SENDC REC2C
```

Sample Calculation of Modal Impedances Z_G, Z_L, Z_{IL}.

Of course the assumed structure of the line-constants matrices of Fig. 2 is an approximation which makes the problem tractable for easy computer solution; it is not really the result which one finds from running the Line Constants Program for any particular double-circuit line. Yet it does provide a reasonably good model for the case of identical circuits supported by different towers, as the following example shows.

Consider two 3-phase 500-kV circuits which are separated by 125 feet (distance between center lines). With each phase consisting of a 3-conductor bundle, and two ground wires per tower, an input data listing as photocopied from the Line Constants Program appears as follows:

```
RECORD OF SORTED INPUT DATA
    PHASE NUMBER R-TYPE RESISTANCE X-TYPE X OR GMR DIAMETER X-COORD. Y-COORD.   NAME
  1      1       .3750   .07760     4    0.00000  1.30200  -21.170   51.040         R-TYPE USED, X OR GMR IGNORED
  2      2       .3750   .07760     4    0.00000  1.30200     .830   79.140         R-TYPE USED, X OR GMR IGNORED
  3      3       .3750   .07760     4    0.00000  1.30200   22.830   51.040         R-TYPE USED, X OR GMR IGNORED
  4      4       .3750   .07760     4    0.00000  1.30200  103.830   51.040         R-TYPE USED, X OR GMR IGNORED
  5      5       .3750   .07760     4    0.00000  1.30200  125.830   79.140         R-TYPE USED, X OR GMR IGNORED
  6      6       .3750   .07760     4    0.00000  1.30200  147.830   51.040         R-TYPE USED, X OR GMR IGNORED
  7      1       .3750   .07760     4    0.00000  1.30200  -22.000   50.000         R-TYPE USED, X OR GMR IGNORED
  8      1       .3750   .07760     4    0.00000  1.30200  -22.830   51.040         R-TYPE USED, X OR GMR IGNORED
  9      2       .3750   .07760     4    0.00000  1.30200    0.000   78.100         R-TYPE USED, X OR GMR IGNORED
 10      2       .3750   .07760     4    0.00000  1.30200    -.830   79.140         R-TYPE USED, X OR GMR IGNORED
 11      3       .3750   .07760     4    0.00000   .30200   22.000   50.000         R-TYPE USED, X OR GMR IGNORED
 12      3       .3750   .07760     4    0.00000  1.30200   21.170   51.040         R-TYPE USED, X OR GMR IGNORED
 13      4       .3750   .07760     4    0.00000  1.30200  103.000   50.000         R-TYPE USED, X OR GMR IGNORED
 14      4       .3750   .07760     4    0.00000  1.30200  102.170   51.040         R-TYPE USED, X OR GMR IGNORED
 15      5       .3750   .07760     4    0.00000  1.30200  125.000   79.100         R-TYPE USED, X OR GMR IGNORED
 16      5       .3750   .07760     4    0.00000  1.30200  124.170   79.140         R-TYPE USED, X OR GMR IGNORED
 17      6       .3750   .07760     4    0.00000  1.30200  147.000   50.000         R-TYPE USED, X OR GMR IGNORED
 18      6       .3750   .07760     4    0.00000  1.30200  146.170   51.040         R-TYPE USED, X OR GMR IGNORED
 19      0       .5000  2.61000     4    0.00000   .38500   12.900  101.040         R-TYPE USED, X OR GMR IGNORED
 20      0       .5000  2.61000     4    0.00000   .38500  -12.900  101.040         R-TYPE USED, X OR GMR IGNORED
 21      0       .5000  2.61000     4    0.00000   .38500  137.900  101.040         R-TYPE USED, X OR GMR IGNORED
 22      0       .5000  2.61000     4    0.00000   .38500  112.100  101.040         R-TYPE USED, X OR GMR IGNORED
```

The resulting impedance matrix [Z] for 50 Hz is then found to be:

```
FOLLOWING MATRICES ARE FOR EARTH RESISTIVITY=  100.00 OHM-M AND FREQUENCY=       50.00 HZ. CORRECTION FACTOR=
                    ************EARTH WIRES WILL BE SEGMENTED ***** *****

                    IMPEDANCE MATRIX (OHM/MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
                         ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

     1.03245E-01
     8.95662E-01

  2  7.59838E-02   1.01856E-01
     4.53672E-01   8.97228E-01

  3  7.65662E-02   7.59844E-02   1.03246E-01
     4.31747E-01   4.53669E-01   8.95656E-01

  4  7.64993E-02   7.58673E-02   7.66138E-02   1.03246E-01
     3.26215E-01   3.42918E-01   3.70026E-01   8.95656E-01

  5  7.57433E-02   7.51370E-02   7.58673E-02   7.59844E-02   1.01856E-01
     3.08823E-01   3.27779E-01   3.42918E-01   4.53669E-01   8.97229E-01

  6  7.61492E-02   7.57433E-02   7.64993E-02   7.65662E-02   7.59838E-02   1.03245E-01
     2.93779E-01   3.08823E-01   3.26215E-01   4.31747E-01   4.53672E-01   8.95662E-01
```

An arithmetic averaging of these elements so as to fit the Fig. 2 model produces the following mean values:

$$\overline{Z_s} = 1.02782\text{E-01} + j8.96182\text{E-01}$$

$$\overline{Z_m} = 7.62115\text{E-02} + j4.46363\text{E-01}$$

$$\overline{Z_p} = 7.60354\text{E-02} + j3.27722\text{E-01}$$

Deviations of the actual values from these mean values then are summarized by the following statistics:

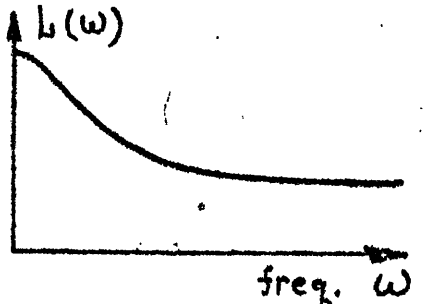
Quantity	Maximum fractional deviation from the sample mean, $\max\left\lvert\frac{Z-\overline{Z}}{\overline{Z}}\right\rvert$	Sample standard deviation as fraction of sample mean, $\frac{\sqrt{\sum (Z-\overline{Z})^2/N}}{\overline{Z}}$
R_s , L_s	0.90% , 0.12%	0.63% , 0.08%
R_m , L_m	0.60% , 3.27%	0.42% , 2.32%
R_p , L_p	1.18% , 9.75%	0.60% , 6.43%

It is the average values just stated which are next converted to modal values, using the formulas of Point 4. One finds .483311 + j2.772074 , .0270988 + j.805742 , and .0265705 + j.449819 for modes "G" , "IL" , and "L" , respectively.

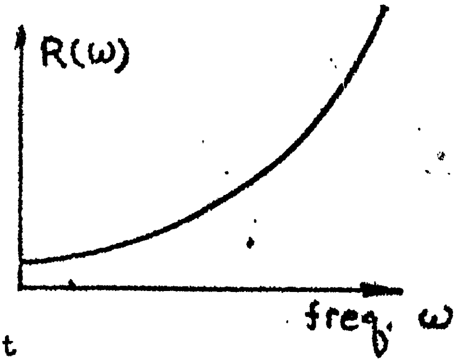
An analogous calculation would of course have to be performed for the capacitance matrix. Then, having modal values for R , L , and C , data cards for the line could be punched as per the preceding Comment 2.

1.26b FREQUENCY DEPENDENCE FOR DISTRIBUTED-PARAMETER LINE

Mathematical theory and implementation details for the inclusion of frequency dependence is covered in Reference 3, so will not be repeated here. This option is an extension of the regular distributed-parameter representation, wherein resistance R and inductance L are assumed constant. Using the frequency-dependence option, the variation of these parameters with frequency is taken into account at the expense of increased storage requirement and running time for every line so modelled. Current usage is typically only for the zero-sequence mode of maybe one or two crucial lines, due to the computational penalty.



If a mode (generally only the zero-sequence mode) is to have frequency dependence included, the following things should be done:



Point 1: Punch a "-1" in columns 53-54 of the branch card corresponding to the mode in question (for zero sequence, this is the first card of the coupled group). Otherwise the card is unchanged. Parameter values punched thereupon should apply at 60Hz, or whatever the sinusoidal steady-state initial frequency may be.

Point 2: Follow the just-mentioned branch card by data cards giving the frequency-dependent characteristics of the mode (as punched out by separate program WEIGHT). These data cards include 3 distinct types of data, as follows:

Type 1 Miscellaneous data card:

1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64
NTIME1	NTIME2	LOCMAX	LOCMIN	ZINF	CUT1	CUT2	LIST
I8	I8	I8	I8	E8.0	E8.0	E8.0	I8

All parameters except "CUT1" , "CUT2" , and "LIST" are automatically punched for the user by the "WEIGHTING" calculation of Section 7.3 (if parameter "IPUNCH" there is given a value of zero or blank). Should the user leave columns 41 onward blank, then the following default values will be assigned for the final three variables: CUT1 = .01 CUT2 = 0.1 LIST = 0 .

NTIME1 —— The number of points defining $a_1(t)$ curve (see below).

NTIME2 —— The number of points defining $a_2(t)$ curve (see below).

LOCMAX —— The point number of the points which define the $a_1(t)$ curve at which the maximum value (positive peak) occurs.

LOCMIN —— The point number of the points which define the $a_2(t)$ curve at which the minimum value (negative peak) occurs.

ZINF — The high (infinite) frequency characteristic impedance Z_1, where

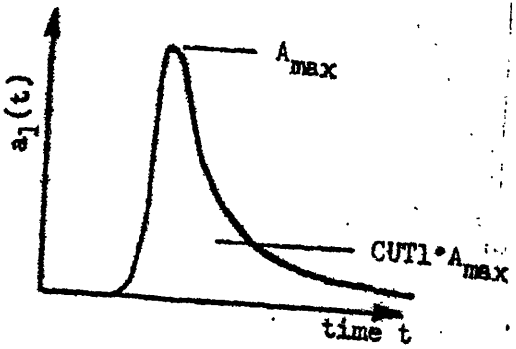
$$Z_1 \triangleq \lim_{\omega \to \infty} \sqrt{L(\omega)/C}$$

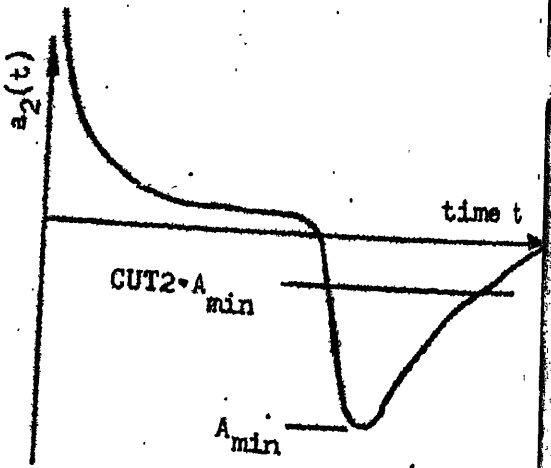
CUT1 — Tolerance defining the fractional decay of $a_1(t)$ from its peak at point NTIME1 after which exponential-tail modelling will be used.

CUT2 — Tolerance defining the fractional decay of $a_2(t)$ from its negative peak at point NTIME2 after which exponential-tail modelling will be used.

LIST — A flag which controls the possible suppression of the input data listing for the cards of weighting functions which may follow

$$\begin{cases} 0 \Longrightarrow & \text{No such suppression; all cards of the following weighting functions (if any) will be listed.} \\ 1 \Longrightarrow & \text{There will be a listing only of the final two data cards of any weighting functions which may follow.} \end{cases}$$





Type 2 Points defining $a_1(t)$

10	20	60	70	80
t_1	$a_1(t_1)$	.... etc	t_4	$a_1(t_4)$
t_5	$a_1(t_5)$		t_8	$a_1(t_8)$
⋮	⋮			

Here the t_i are time-point values in microseconds. The format is 4(I10, F10.0), for as many cards as are needed to define the nonzero part of the curve. The points t_i are assumed to be in increasing order, and no blank termination card is used.

Type 3 Points defining $a_2(t)$

10	20	60	70	80
t_1	$a_2(t_1)$	.... etc	t_4	$a_2(t_4)$
t_5	$a_2(t_5)$		t_8	$a_2(t_8)$

⋮

Same format as Type 2. The first point of $a_2(t)$ should be for time $t = t_1 = 0.0$, though.

As a very crude (generally within ∓ 50%) estimate of the number of weighting -function points required for the zero sequence of a transmission line, use the formula:

$$NP = 6\tau/\Delta t$$

where τ is the zero sequence travel time of the line. Here we are considering the size of list 14, Section 0.6 . Any lines which do not have a characteristic of their own, but rather use the reference branch idea (fields BUS3, BUS4 on the branch card for the zero sequence), do not contribute anything to the total requirement for list 14.

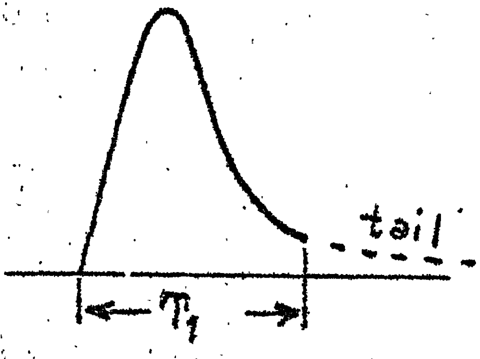
A more exact calculation for the size of list 14 requires reference to the weighting functions $a_1(t)$ and $a_2(t)$ as shown on the preceding page. Let

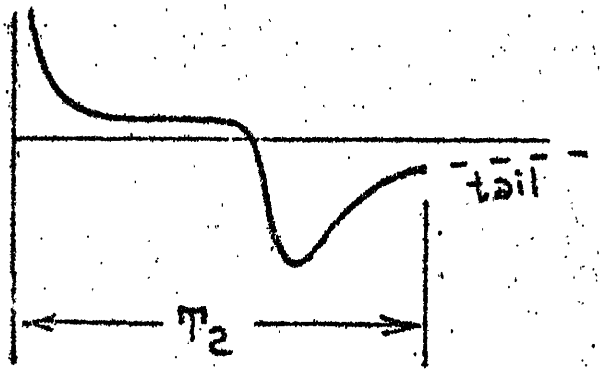
T_1 = time over which $a_1 > 0$, but has not yet reached the cutoff value of the exponential tail.

T_2 = time of cutoff of a_2 , after which the tail begins for a_2 (using exponential tail modelling).

Then a more precise approximation to the weighting function storage requirement is given by

$$NP = (T_1 + T_2) / \Delta t$$





1.2X Recursive Convolution Frequency Dependence

Modal wave propagation for overhead lines has a frequency response characteristic resembling that of a low-pass filter in series with a pure time delay τ . figure A below is typical. Characteristic

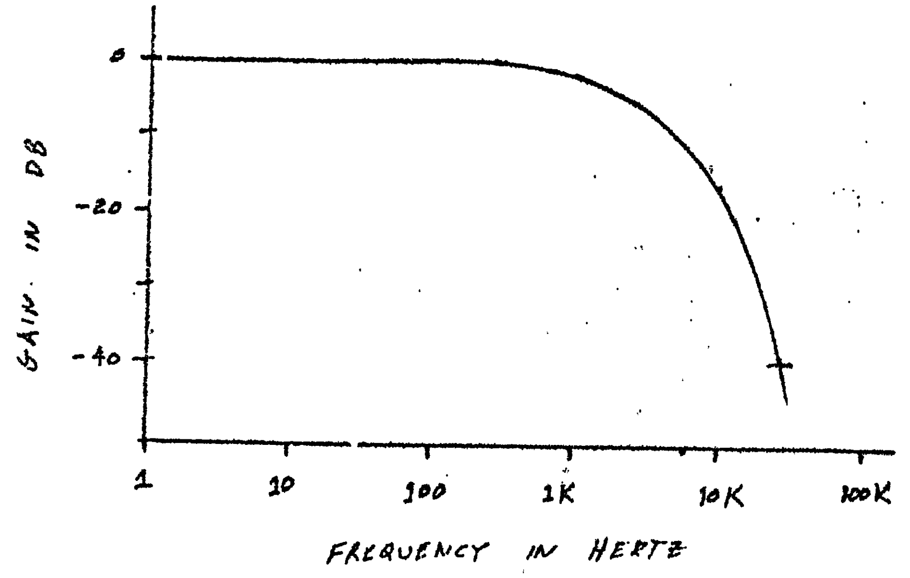


Figure A. Typical gain response for wave propagation

admittance, on the other hand, exhibits an inital $\sqrt{f}$ behavior up to a "knee" somewhere around 1Hz. (Figure B). The upper modes often have y_c essentially constant above 10Hz. For mode 1, however, y_o may roughly double between 10Hz and response data cutoff (at -40 db).

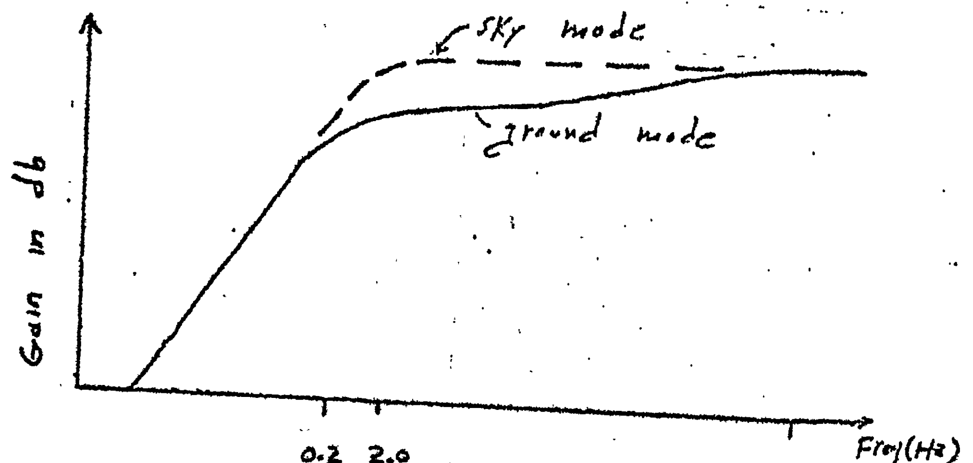


Figure B. Typical gain response for characteristic admittance

Models for wave propagation and characteristic admittance are specified by τ and the transfer function

$$T(s) = \frac{G(s-z_1)\ \cdots\ (s-z_m)}{(s-P_1)\ \cdots\ (s-P_n)} \qquad (1A)$$

$$= K_{ff} + \sum_{\ell} \frac{K_\ell}{(s-P_\ell)} \qquad (1B)$$

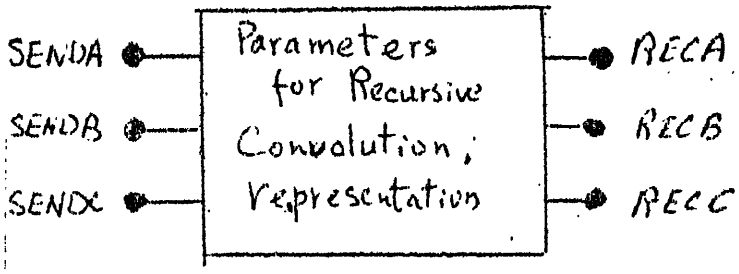
$$= K_{ff} + \sum_{l} \frac{\hat{K}_l / P_l}{(s-P_l)} \qquad (1C)$$

where Z_l ; P_l are the zeros and poles of T(s); K_l and $\hat{K}_l$ are the residues of T(s) for impulse and step inputs respectively.

For the wave-propagation model the feedforward coefficient K_{ff} is zero, and τ is approximately the line travel time. The admittance model has $\tau = 0$, and K_{ff} approximates the high-frequency value of Y_0. Following "SEMLYEN SETUP" conventions, each transfer function is represented on cards by partial-fraction expansion (Eq. 1c).

1.27a Data Requirements for Recursive Convolution Representation

The original Recursive Convolution modeling code was contributed by Ontario Hydro of Toronto, Ontario, Canada. Please see Section 0.2, item 2 for additional information.



Suppose that the user wants to specify an N-conductor distributed-parameter transmission circuit which is modeled using Recursive Convolution. He should first procure the punched-card output of a "SEMLYEN SETUP" or a "HAUER SETUP" run which corresponds to the geometry (including line length and ground resistivity) and steady-state frequency of interest. A full discussion will be found in Section 7.5 and 7.8 respectively. (As explained in Section 7.6, the rules will not be given for Recursive Convolution Representation using the straight-line segments fitting technique, i. e. "AMETANI SETUP".) Such cards will hopefully conform to the following rules:

Rule 1: There is to be a branch card for each phase (mode), punched according to the following format:

ITYPE	BUS1	BUS2	y_0	τ	N1	N2	N3	N4	N5	IOUT
I2	A6	A6	E12.5	E12.5	I3	I3	I3	I3	I4	I1

ITYPE = -1 ---- Type code for branch.

BUS1 } ---- Six-character alphanumeric node names. The
BUS2 } sending and receiving ends of the branch under consideration are to be connected to these two network nodes, respectively.

Y_0 ---- Infinite-frequency characteristic admittance (K_{ff} in Eq. 1c) τ ---- travel time

N1 }
N2 } ---- For the K-th mode (phase), N1 = N2 = K.

N3 ---- The number of exponential curves used in the propagation step response fitting.

N4 ---- The number of exponential curves used in the characteristic admittance fitting.

N5 ---- The number of coupled conductors (or modes) making up this transmission circuit.

IOUT ---- Used to control the availability of branch variabels for printing and/or plotting. As usual,

"1"-punch produces branch current output;
"2"-punch produces branch voltage output;
"3"-punch produces both branch current & voltage;
"4"-punch produces branch power and energy consumption (see Section 1.8).

Rule 2: The just-delineated branch (mode) card is to be immediately followed by a card with steady-state information:

	R(ω)	ωL(ω)	G(ω)	ωC(ω)	FREQ
2X	E15.8	E15.8	E15.8	E15.8	E15.8

R }
ωL } ---- Total series modal impedance for mode number N1. This is in ohms, at the frequency FREQ of the steady-state phasor solution which may be performed to find EMTP initial conditions. By definition, these total impedance values are equal to the incremental values (in ohms per unit length) multiplied by the line length.

G }
ωC } ---- Total shunt modal admittance for mode number N1. This is in mhos, at the frequency FREQ of the steady-state phasor solution which may be performed to find EMTP initial conditions. By definition, these total admittance values are equal to the incremental values (in mhos per unit length) multiplied by the line length.

FREQ ---- the steady-state frequency

Rule 3: After the second card, then come a number of cards which characterize the wave propagation and characteristic admittance responses. These cards have the followig format:

	VOLT(1)	VOLT(2)	VOLT(3)	VOLT(4)	VOLT(5)	VOLT(6)
2X	E12.5	E12.5	E12.5	E12.5	E12.5	E12.5

Each of these cards specifies two partial fractions (See Eq. 1c). Let the mth pole P_m be defined as $P_m = -\sigma_m + j\omega_m$, where both σ_m and ω_m are positive, and let the corresponding residue $\hat{K}_m$ be defined as $\hat{K}_m = \hat{K}_{r,m} + \hat{K}_{i,m}$. Then two real poles P_m and P_{m+1} can be specified on one such card where

$$\mathrm{VOLT}(1) = 0.0, \quad \mathrm{VOLT}(2) = \sigma_m, \quad \mathrm{VOLT}(3) = -\hat{K}_{r,m}$$
$$\mathrm{VOLT}(4) = 0.0, \quad \mathrm{VOLT}(5) = \sigma_{m+1}, \quad \mathrm{VOLT}(6) = -\hat{K}_{r,m}$$

On the other hand, one whole card is needed for each of the complex pole P_m :

$$\mathrm{VOLT}(1) = 1.0, \quad \mathrm{VOLT}(2) = \sigma_m, \quad \mathrm{VOLT}(3) = -\hat{K}_{r,m}$$
$$\mathrm{VOLT}(4) =-1.0, \quad \mathrm{VOLT}(5) = -\omega_m, \quad \mathrm{VOLT}(6) = \hat{K}_{i,m}$$

Rule 4: The cards under Rules 1, 2, and 3 are repeated for each branch (or phase or mode), in order.

Rule 5: Following the cards of Rule 4 are to come records which define the voltage transformation matrix $[T_V]$, where

$$\vec{V}_{phase} = [T_V] \cdot \vec{V}_{mode}$$

Complex Matrix elements are inputted by rows, in natural order (row #1 first, then row #2, etc.) and are in terms of the real and imaginary pairs. However, the imaginary part of each element is set to be zero. Within any row, elements are inputted in order of increasing column number. Each row begins with a new card, and there are six or fewer numbers per card. The following format is applicable to row "K" for a 3-phase transmission circuit:

$TV^R_{K,1}$	$TV^I_{K,1}$	$TV^R_{K,2}$	$TV^I_{K,2}$	$TV^R_{K,3}$	$TV^I_{K,3}$
E12.5	E12.5	E12.5	E12.5	E12.5	E12.5

Rule 6: Following the cards of Rule 5, there is a second such grouping, only for the current transformation matrix [T], where

$$\vec{I}_{phase} = [T_i] \quad \vec{I}_{mode}$$

The number of elements and their ordering is identical to that for the voltage transformation matrix, which has just been described.

$TI^R_{K,1}$	$TI^I_{K,1}$	$TI^R_{K,2}$	$TI^I_{K,2}$	$TI^R_{K,3}$	$TI^I_{K,3}$
E12.5	E12.5	E12.5	E12.5	E12.5	E12.5

Rule 7: The column-80 punch on the branch cards (see "IOUT" of Rule 1) must always be supplied by the user, if branch output variables for a Recursive Convolution line are desired. The punched-card output of "SEMLYEN SETUP" OR "HAUER SETUP" will always leave column 80 of the branch cards blank(corresponding to no such output).

16c-5

An example of punched output from running "HAUER SETUP":

```
C    1.3636 .05215  4          1.602  -20.75   50.    50.
C    1.3636 .05215  4          1.602  -19.25   50.    50.
C    2.3636 .05215  4          1.602   -0.75   77.5   77.5
C    2.3636 .05215  4          1.602    0.75   77.5   77.5
C    3.3636 .05215  4          1.602   19.25   50.    50.
C    3.3636 .05215  4          1.602   20.75   50.    50.
C    0.5    2.61    4          0.386  -12.9    98.5   98.5
C    0.5    2.61    4          0.386   12.9    98.5   98.5
C
C  27.         60.           1                   138.
C  27.         6.0           1                   138.
C                                                                9 20
-1BEGINAEADA                0.16087E-02 0.74835E-03                   1  1 14  2
  0.67519497E+02 0.22868008E+03 0.00000000E+00 0.62996594E-03 0.60000000E+0
 0., 0.332724400E+03, 0.505695145E-01,  0., 0.618279420E+03, 0.748306243E
 0., 0.120336237E+04, 0.227732022E+00,  0., 0.827371563E+04,-0.5972452
 0., 0.900430932E+04, 0.249999225E-01,  0., 0.159807707E+05, 0.375169389
 0., 0.194752175E+05, 0.117242152E+00,  0., 0.365005345E+05, 0.548528416
 0., 0.654814465E+05,-0.150033701E+01,  0., 0.212800153E+06, 0.120734101E
 0., 0.271630247E+05,-0.185580739E+05,  0., 0.273142633E+06, 0.212711428E
 0., 0.275102179E+05,-0.160603504E+05,  0., 0.287226371E+06, 0.351251972
 0., 0.000000000E+00, 0.000000000E+00,  0., 0.000000000E+00, 0.000000000E
-1BEGINBEADA                0.35256E-02 0.74318E-03                   2  2 14  2
  0.40944359E+01 0.80845419E+02 0.00000000E+00 0.10069636E-02 0.60000000E+0
 0., 0.827674470E+03, 0.399806056E-01,  0., 0.130501996E+06, 0.508365787E
 0., 0.252780509E+06,-0.280985589E+00,  0., 0.260749831E+06, 0.360866589
 0., 0.544371051E+06,-0.152545223E+01,  0., 0.696229069E+06, 0.773993647
 0., 0.768151125E+06,-0.566855564E+01,  0., 0.415043368E+07,-0.224486177
 0., 0.896130666E+07,-0.180297330E-02,  0., 0.104572655E+07, 0.286577225
 0., 0.118008019E+08,-0.243527045E+05,  0., 0.119761142E+08, 0.200319291E
 0., 0.120014677E+08,-0.177347435E+06,  0., 0.125804003E+08, 0.111275201E
 0., 0.000000000E+00, 0.000000000E+00,  0., 0.000000000E+00, 0.000000000E
-1BEGINCEADA                0.35256E-02 0.74318E-03                   3  3 14  2
  0.40944359E+01 0.80845419E-02 0.00000000E+00 0.10069636E-02 0.60000000E+0
 0., 0.827674470E+03, 0.399806056E-01,  0., 0.130501996E+06, 0.508365787E
 0., 0.252780509E+06,-0.280985589E+00,  0., 0.260749831E+06, 0.360866583E
 0., 0.544371051E+06,-0.152545223E+01,  0., 0.696229069E+06, 0.773993647E
 0., 0.768151125E+06,-0.566855564E+01,  0., 0.415043368E+07,-0.224486177E
 0., 0.896130666E+07,-0.180297330E+02,  0., 0.104572655E+08, 0.286577225E
 0., 0.118003015E+08,-0.243527045E+05,  0., 0.119761140E+08, 0.200319291E
 0., 0.120014677E+08,-0.177347435E+06,  0., 0.125804003E+08, 0.111275201E
 0., 0.000000000E+00, 0.000000000E+00,  0., 0.000000000E+00, 0.000000000E+0
 0.57735026919E+00, 0., 0.70710678119E+00, 0., 0.40824829046E+00, 0.
 0.57735026919E+00, 0.,-0.70710678119E+00, 0., 0.40824829046E+00, 0.
 0.57735026919E+00, 0., 0.00000000000E+00, 0.,-0.81649658093E+00, 0.
 0.57735026919E+00, 0., 0.70710678119E+00, 0., 0.40824829046E+00, 0.
 0.57735026919E+00, 0.,-0.70710678119E+00, 0., 0.40824829046E+00, 0.
 0.57735026919E+00, 0., 0.00000000000E+00, 0.,-0.81649658093E+00, 0.
```

1.28 Branch Cards for Pseudo-Nonlinear Resistance (Type-99 Element)

The true nonlinear v-i characteristic of Section 1.32 has limited usage due to the required travel time separating such elements. It is because such a true nonlinear representation can not then be used for more than one phase of a 3-phase nonlinearity that the element now to be described was developed. The element to be described seems to generally be a good approximation to the true nonlinear characteristic, provided the user exercises caution in employing it.

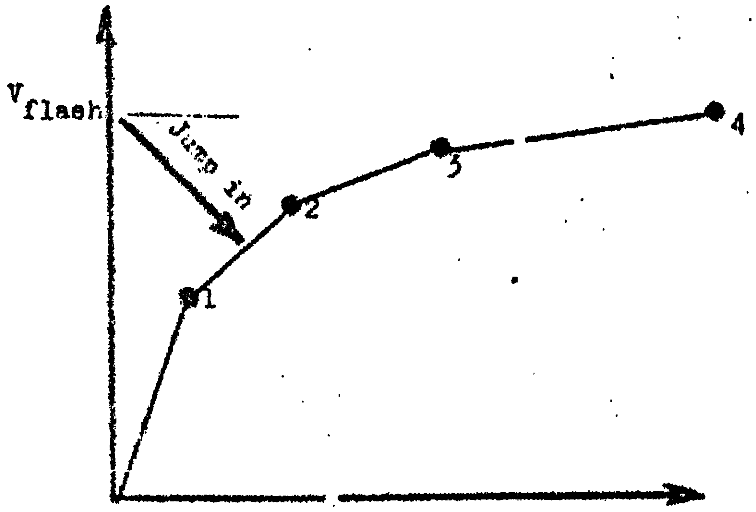


Fig. 1. Nonlinear v-i characteristic, with flashover.

Conceptually, the idea is very simple. Since any segment of the piecewise-linear v-i curve is a straight line (see Fig. 1), such a segment can be represented in the program by a resistor in parallel with the appropriate current source (see Fig. 2). The only problem is with limits, which of course are not observed by the linear representation of Fig. 2. We do not have a true (simultaneous) nonlinearity, and must rely on past history to tell us on what segment we should operate. In particular, the following points apply:

1. Upon flashover, there is no relevant history; the user must specify which segment he thinks it is appropriate to jump in on (see Fig. 1).

2. The user must use a small enough time step so that one moves up and down the nonlinearity slowly, smoothly. The program will only change segments after having illegally operated outside the range of the current segment for one time step, note (see Fig. 3).

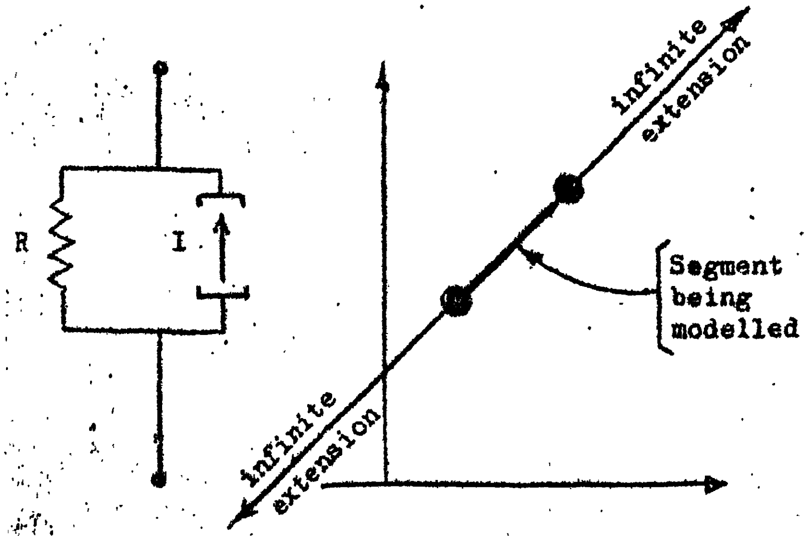


Fig. 2. Linear approximation used in program.

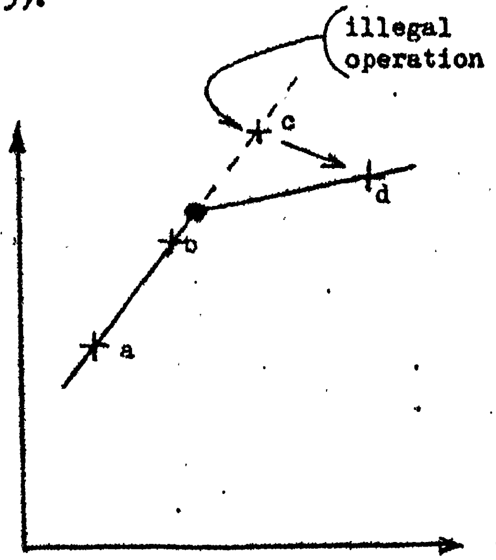
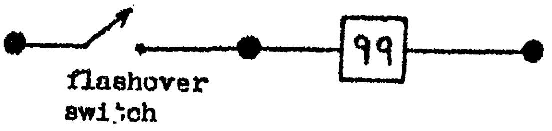


Fig. 3. Sample movement to a high r segment.

So as to avoid connectivity difficulties (see Section 1.3-D), the program automatically inserts a very-high-impedance resistive branch in parallel with a type-99 element, should no parallel branch exist as part of the user's data. This branch should have negligible effect on the answers, while sparing the user from the necessity of manually inserting such elements so as to provide the necessary connectivity.

The user must exercise care so as to always set up a physically-realistic problem. For example, the series connection of two type-99 elements is absurd, since mathematically there is no way to determine the voltage split between the two perfect gaps; the problem is not even defined. The same holds true of the series connection of a type-99 element and a flashover switch. Be nice to the program, and the program will be nice to you.



Rules for Data Input of type-99 element

1) Branch type is $\boxed{99}$ (field ITYPE; columns 1-2).

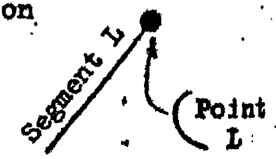
2) Specify the terminal nodes by name (fields BUS1 and BUS2; columns 3-14). One node may be grounded, if desired (blank for node name).

3) If the v-i characteristic proper (exclusive of VFLASH, TDELAY, and JUMP) is identical with a preceding type-99 element, use the following storage saving option: Punch the node names of that preceding reference branch in fields BUS3 and BUS4 (columns 15-26), and omit the cards defining the v-i characteristic as mentioned in Point 8 below.

4) Field VFLASH specifies the breakdown voltage for the branch; until terminal voltage exceeds this figure in absolute value, a type-99 element is an open circuit. Such an open circuit is assumed for the steady state solution also.

5) The element will open up again after having been conducting when a current zero occurs (see illustration of Sect. 1.40), provided a time interval of TDELAY seconds has elapsed since the most recent firing (initiation of conduction as per Point 4). It is assumed that such a polarity change will occur only while operation is on segment 1 (that passing through the origin); if the polarity change occurs while operating on higher segments, a warning message of "TROUBLE" will be printed out (see Sect. 2.2b , Message 18).

6) Field JUMP gives the segment number that is to be jumped in on upon flashover. Segment L is, by definition, the one having point L (see Fig. 1 numbering) at its upper end, as shown in the sketch. A zero (or blank) field is automatically converted to a default value of unity.



7) Output options for printing and/or plotting use field IOUT in column 80:

1-punch produces branch current
2-punch produces branch voltage
3-punch produces both branch current and branch voltage
4-punch produces branch power and energy consumption (see Section 1.8)

8) The v-i characteristic is defined point by point on cards which immediately follow the aforementioned branch card; these points are terminated by a 9999-card (punched in columns 13-16).

a) The origin of the characteristic (i=0, v=0) is an implied point, which must not be inputted explicitely.

b) Current and voltage pairs of the break points are punched in fields CUR and VOLT, columns 1-32, one pair of values per card.

c) The order of input of points is as per Fig. 1, where both current and voltage values must be strictly monotone increasing. Thus segments with negative, zero, or infinite slope are not allowed.

No problem with spilling off the end of the curve exists, as the program assumes that the final two points define a segment which extends to infinity.

First Card Format

1-2	3-8	9-14	15-20	21-26	27-32	33-38	39-44	45-50		80
ITYPE	Node names		Reference br.		VFLASH	TDELAY	JUMP	VSEAL	•	IOUT
	BUS1	BUS2	BUS3	BUS4						
I2	A6	A6	A6	A6	E6.0	E6.0	I6	E6.0		I1

Format for Points of V-I Characteristic

1-16	17-32
CUR	VOLT
E16.0	E16.0

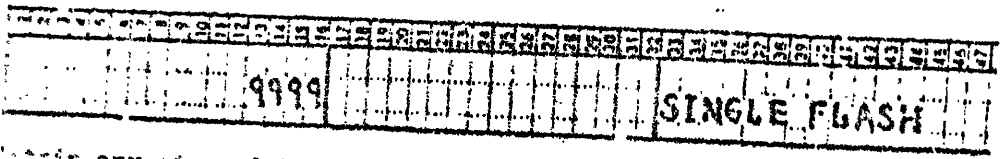
1-16
9999

Sample Data Listing

```
99ALPHA BETA               1.2E5  .065     3
             1.0          50000.
             3.0         100000.
            10.0         300000.
            30.0         500000.
            9999
99TESLA       ALPHA BETA   1.1E5           2
```

If the user only wants to allow a type-99 element to flash over once, he can use the "SINGLE FLASH" option. This is governed by the following special rules and restrictions:

a) The key word "SINGLE FLASH" is to be punched in columns 33-44 of the 9999-card which terminates the i-v characteristic of the element in question:

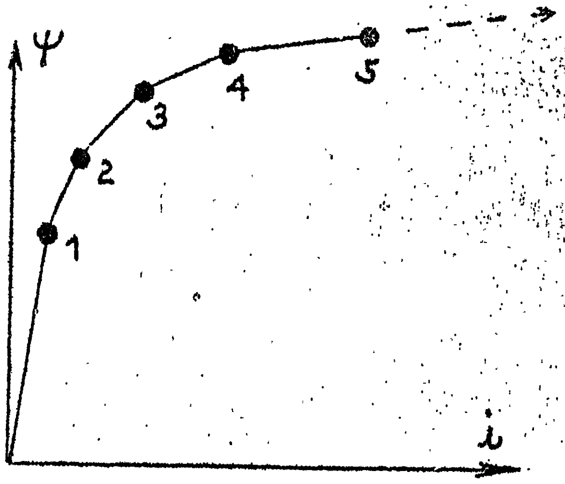


b) Within any given data case, the "SINGLE FLASH" request is only to be punched once, on the 9999-card of the first such type-99 element which is inputted. Any other type-99 element whose characteristic has the same first breakpoint voltage V_1 as this first one so flagged will also be allowed to flash a maximum of just one time. Thus, in particular, any number of identical type-99 elements can all be treated as single-flash units.

Except for the prohibition against flashing a second time, such "SINGLE FLASH" type-99 elements are identical to conventional type-99 elements.

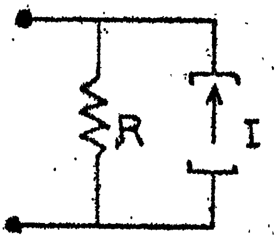
[illegible]) Data field "VSEAL" of columns 45-50 is normally left blank, which then provides for opening (current interruption) on current zero. But sometimes the user wants to open the circuit before a zero crossing on the current. This is possible, if "VSEAL" is punched positive, indicating a voltage threshold (sealing-off voltage) below which conduction is not allowed.

1.29 Branch Card for Pseudo-Nonlinear Reactor (Type-98 Element)



The true nonlinear flux-current characteristic of Section 1.33 has limited usage due to the required travel time which must separate such elements; it cannot, for example, be used in 3-phase configurations, which are the common cases of interest. Because of this restriction, the present pseudo-nonlinear reactor has been developed ---- an element which may be placed anywhere.

The pseudo-nonlinear reactor is the inductive analog of the pseudo-nonlinear resistance of Section 1.28, using a parallel connection of resistor and current source for internal representation (see sketch); resistance R changes only when operation moves from one segment of the characteristic to another, while the current source is updated at each time step. The qualification "pseudo" has been appended because operation moves from one segment to another only after having illegally operated outside the range of the present segment for one time step (Fig. 3, Sect. 1.28).



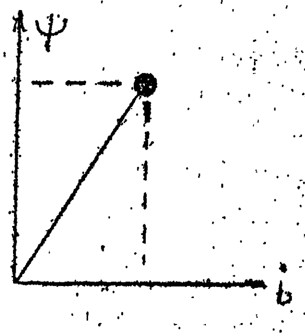
Rules for data input of type-98 element

1) Branch type is $\boxed{98}$ (field ITYPE; columns 1-2).

2) Specify the terminal nodes by name (fields BUS1 and BUS2; columns 3-14). One node may be grounded, if desired (blank field for node name).

3) If the i-Ψ characteristic proper (exclusive of i_{steady} and Ψ_{steady}) is identical with a preceding type-98 element, use the following storage-saving option: Punch the node names of the preceding reference branch in fields BUS3 and BUS4 (columns 15-26), and omit the cards defining the i-Ψ characteristic as mentioned in Point 6 below.

4) Fields i_{steady} and Ψ_{steady} (columns 27-38) define the constant linear inductance to be used during the sinusoidal, phasor, steady-state solution. While only the ratio is actually required ($L = \Psi / i$), Ψ_{steady} is taken to be the limit on the linear region of operation; if initial flux exceeds this value, the T.P. prints out a warning message after the steady-state solution (see Sect. 2.2b, Message 15).



5) Output options for printing and/or plotting use field IOUT of column 80:

1-punch produces branch current output
2-punch produces branch voltage output
3-punch produces both branch current and branch voltage
4-punch produces branch power and energy consumption (see Sect. 1.8)

Node names		Reference br.		i_{steady}	ψ_{steady}	● ● ●	IOUT
BUS1	BUS2	BUS3	BUS4				
A6	A6	A6	A6	E6.2	E6.2		I1

The i-ψ characteristic is defined point by point, on cards which immediately follow the aforementioned branch card; these points are terminated by a 9999-card (punched in columns 13-16).

a) The origin of the characteristic (i=0, ψ=0) is an implied point, which must not be inputted explicitely.

b) Current and flux pairs of the break points are punched in fields CUR and FLUX (columns 1-32), one pair of values per card.

c) The order of input of points is as per numbering on the sketch, where both current and flux values must be strictly monotone increasing.

d) Usually the first point of the characteristic will equal (i_{steady}, ψ_{steady}), in order to provide continuity between steady-state and transient solutions at time zero, though such matching is not mandatory.

CUR	FLUX
E16.0	E16.0

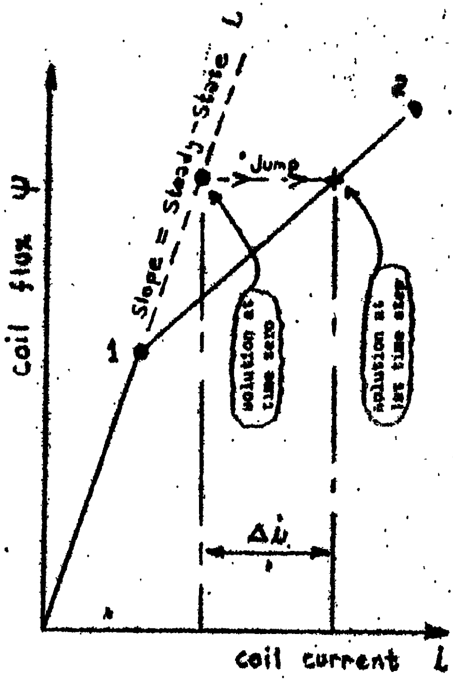
9999

Sample Data Listing

```
  ALPHA BETA                    21.3 249.1
            21.3           249.1
            99.8           274.0
           236.9           288.9
           1602.           326.3
            9999
  TESLA       ALPHA BETA
```

Caution concerning possible discontinuity at time zero

The user should always keep in mind that the sinusoidal steady-state phasor solution involves the linear magnetizing inductance given by $L = \psi_{steady} / i_{steady}$. Yet at the first time step, the EMTP shifts to using the user-defined nonlinear characteristic, at present always starting out on the first segment. If the initial-condition point does not lie on the characteristic, there will be a discontinuity which may produce a spurious transient immediately after time zero. Flux is always continuous, so the adjustment is accomplished by a horizontal jump having current discontinuity Δi , as per the sketch. If only one segment change is required as shown, this occurs in one time step. Hence a connected inductor of value L_s might well experience a corresponding voltage change of something on the order of $L_s \Delta i / \Delta t$, which may be substantial for small time steps (many per unit, in extreme cases). Present EMTP logic only allows one segment change per time step, so if the ultimate operating point really is on the K-th segment, K-1 time steps would be required to effect the total adjustment process, during which time a spurious transient of unpredictable shape might be observed.



For balanced 3-phase initial conditions, the user can always shift his time reference (rotate the phase angles of all sinusoidal sources by some fixed phase angle) so that none of the three initial fluxes (or alternatively, currents) exceeds $\sqrt{3}/2 \cong .866$ times its peak value. In terms of figures which can be read from the phasor steady-state solution printout of branch flows, this corresponds to shifting the time origin so that current in one of the three components (for the 3-phase representation) is exactly zero at time zero.

The intelligent user will learn to always check the initial flux in type-98 pseudo-nonlinear inductors, and be wary of the aforementioned possible discontinuity. The initial flux in all data-case nonlinear or pseudo-nonlinear coils is printed out after the complete steady-state solution, and before the time-step-loop column headings, with a sample being:

```
INITIAL FLUX IN COIL 'JOHNDA' TO 'INTA  ' = E13.5
```

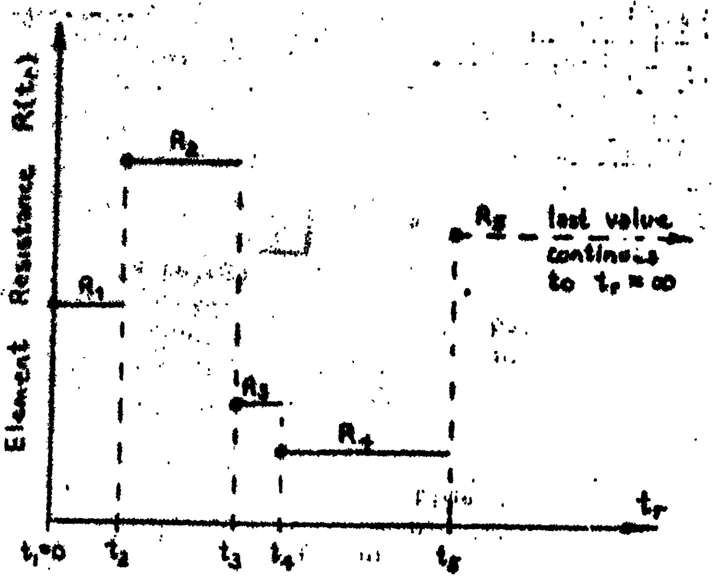
Assuming that the user has picked i_{steady} and ψ_{steady} equal to coordinates of the first point of the characteristic, then the aforementioned discontinuity trouble will be signaled by the following additional message:

```
WARNING.  ASSUMPTION THAT AC STEADY STATE HAS FUNDAMENTAL FREQUENCY ONLY IS
          QUESTIONABLE WITH PRECEDING FLUX OUTSIDE LINEAR REGION.
```

Whenever the user sees such a message, he should be careful, and should study what the effect on the network solution will be; if possible, it is of course desirable to make legitimate alterations which cause all such messages to disappear.

1.30 Branch Card for Staircase Time-Varying Resistance R(t) (type-97 element)

The continuous time-varying resistor R(t) of Section 1.31 has limited usage, due to the required travel time which must separate such elements; it cannot, for example, be used in 3-phase configurations, which are the common cases of interest. Because of this restriction, the present staircase time-varying resistance element has been developed ------ an element which may be placed anywhere, in any numbers.



Time element has been connected to network, t_r

Rules for type-97 data input

1) Branch type is $\boxed{97}$

This is punched in field ITYPE , columns 1-2 .

2) Specify the terminal nodes of the branch by name (fields BUS1 and BUS2 , columns 3-14). One node may be grounded if desired (indicated by blank field for node name in question).

3) If the $R(t_r)$ characteristic proper (exclusive of VFLASH and TDELAY) is identical to that of a preceding type-97 element, use the following storage-saving option: Punch the node names of the preceding reference branch in fields BUS3 and BUS4 (columns 15-26), and omit the cards defining the $R(t_r)$ characteristic as mentioned in Point 6 below.

4) Data fields VFLASH and TDELAY determine at what time during the simulation the element is to be connected. The possibility of either a fixed time delay, or of a delay dependent upon the appearance of a minimum flashover voltage, is provided for by appropriately punching columns 27-38.

$$\text{VFLASH} \text{ ------ } \begin{cases} 0 \Rightarrow \text{no flashover delay} \\ V_f \Rightarrow \text{with } V_f > 0 \text{, the element is not connected until the branch terminal voltage } v \text{ satisfies } |v| > V_f . \end{cases}$$

1 2	3 4 5 6 7 8	9 10 11 12 13 14	15 16 17 18 19 20	21 22 23 24 25 26	27 28 29 30 31 32	33 34 35 36 37 38		80
ITYPE	Node names		Reference br.		VFLASH	TDELAY	• • •	IOUT
	BUS1	BUS2	BUS3	BUS4				
I2	A6	A6	A6	A6	E6.0	E6.0		I1

16kV

TDELAY -----

- -1 ⇒ The first-step resistance value R_1 is assumed to be present for all time $t < 0$, as part of the sinusoidal phasor solution. Element time t_r and simulation time t are identical; field VFLASH is disabled.
- 0 ⇒ No such special fixed time delay (there may be delay due to positive VFLASH, though). Element is not connected for steady-state phasor solution.
- T_d ⇒ With $T_d > 0$, the element will never be connected until the simulation time t reaches this delay value. Positive VFLASH may provide added delay beyond this point, until such time as the branch voltage then exceeds the flashover value.

5) Output options for printing and/or plotting use field IOUT of column 80, as follows:

1-punch produces branch-current output;
2-punch produces branch-voltage output;
3-punch produces both branch-current and branch-voltage output;
4-punch produces branch-power and energy-consumption outputs (see Section 1.8).

6) The R(t) characteristic is defined point by point, on cards which immediately follow the aforementioned branch card; these points are terminated by a 9999-card (punched in columns 13-16).

a) The beginning of the characteristic, at time $t_r = 0$, is the first point to be inputted.

b) Time and resistance pairs defining each step of the staircase characteristic are punched in fields TIME and RESIS (columns 1-32), one pair of values per card.

TIME	RESIS
E16.0	E16.0

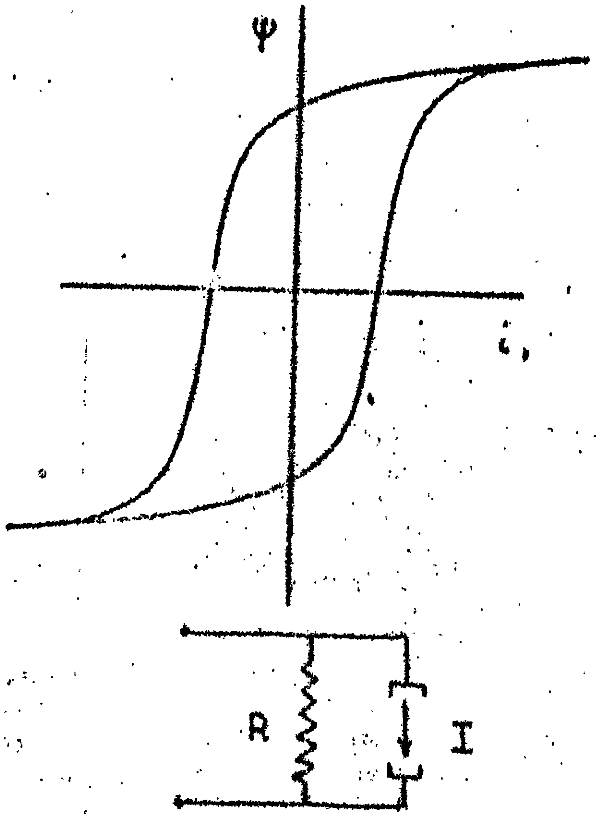
c) The order of input for points of the characteristic must be as per the numbering on the sketch, with time in seconds being monotone increasing. All resistance values must be positive, in units of [voltage/current] (ohms, if in MKS system).

d) The last point is followed by the 9999-card.

9999

1.31 Branch Card for Pseudo-Nonlinear Hysteretic Reactor (Type-96 Element)

The pseudo-nonlinear hysteretic inductor is very similar to the pseudo-nonlinear inductor described in section 1.29. The major difference is that this element allows the hysteretic behavior of the core material to be represented. The element is represented internally by a resistor in parallel with a current source (see sketch). The resistance R is changed only when operation moves from one segment to another, whereas the value of the current source is updated at each time step. The qualification "pseudo" has been applied because operation moves from one segment to another only after having illegally operated outside the range of the present segment for one time step (Fig. 3, sect. 1.28).



Rules for Data Input of Type-96 Element

1) Branch type is $\boxed{96}$ (field ITYPE; columns 1-2).

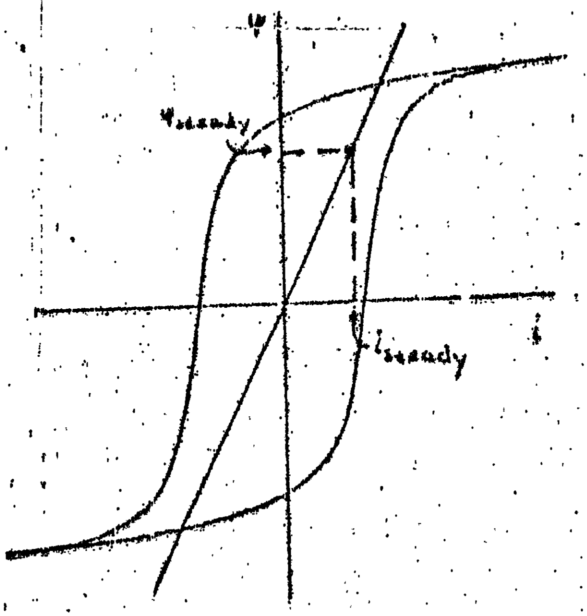
2) Specify the terminal nodes by name (fields BUS1 and BUS2; columns 3-14). One node may be grounded, if desired (blank field for node name).

80

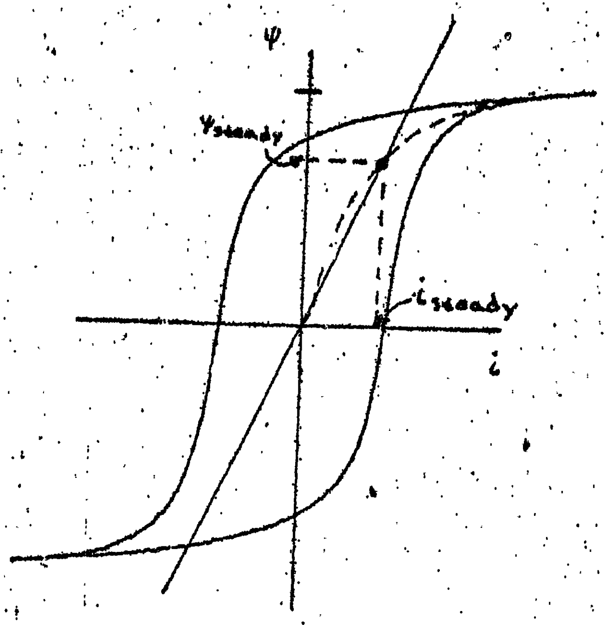
Type	Node names		Reference br.		i_{steady}	ψ_{steady}	ψ_{res}	...	IOUT
	BUS1	BUS2	BUS3	BUS4					
I2	A6	A6	A6	A6	E6.2	E6.2	E6.2		I1

3) If the i-ψ characteristic proper (exclusive of i_{steady}, ψ_{steady}, and ψ_{res}) is identical with one of the preceding type-96 elements, use the following storage saving option: Punch th node names of the preceding reference branch in fields BUS3 and BUS4 (columns 15-26) and omit the cards defining the i-ψ characteristic as mentioned in point 6 below.

4) Fields i_{steady} and ψ_{steady} (columns 27-38) define the constant linear inductance to be used during the sinusoidal, phasor, steady-state solution. While only the ratio is actually required ($L = \psi_{steady}/i_{steady}$), ψ_{steady} is taken to be the limit on the linear region of operation; if initial flux exceeds this value, the EMTP prints out a warning message after the steady-state solution (see Sect. 2.2b, message 15). In addition, the point (i_{steady}, ψ_{steady}) must lie within the major hysteresis loop. If it does not, the EMTP will halt this run, providing an error message indicating this mistake.



The user also has the option of allowing the EMTP to calculate i_{steady} and ψ_{steady} itself. This option is chosen by specifying i_{steady} = 8888. and leaving ψ_{steady} blank. The EMTP chooses the steady-state point as follows: first the trajectory from the origin to the positive saturation point is created, then the point on that trajectory where the flux is equal to 70% of the saturation flux is chosen as the steady-state point (see sketch).



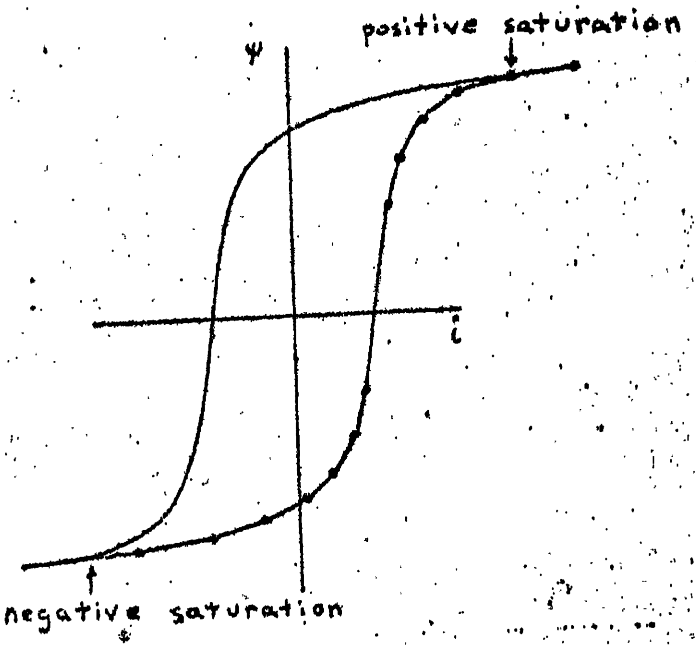
5) Field ψ_{res} (columns 39-44) specifies the value of residual or remnant flux in the core. This will be used as the initial value of flux ($\psi(0)$) in the coil provided a non-zero flux value is not calculated for time zero by a sinusoidal, phasor, steady-state solution.

Therefore, if this type-96 element is not connected during a steady-state solution, the value of flux in the coil at time zero will be taken as the value specified in the field ψ_{res}. If this type-96 element is connected during a steady-state solution and only if the value of flux at time zero determined by the phasor solution is zero, the value of flux specified in the field ψ_{res} is used as the initial flux at time zero. (Note that if ψ_{res} = 0, the initial flux at time zero will be identical to that calculated by the phasor solution). Otherwise the initial flux in this type-96 element will be taken as the value calculated from the steady-state solution.

The value of ψ_{res} which is specified must lie within the major loop, otherwise the EMTP will print an error message indicating the mistake and halt the present job being run.

6) Output options for printing and/or plotting use field IOUT of column 80.
   1 - punch produces branch current output
   2 - punch produces branch voltage output
   3 - punch produces both branch current and branch voltage
   4 - punch produces branch power and energy consumption (se sect. 1.8)

7) The i-ψ characteristic is defined point by point, on cards which immediately follow the aforementioned branch card; these points are terminated by a 9999 - card (punched in columns 13-16).
   a) The bottom half of the loop must be defined - the top half is then determined by symmetry.



b) Current and flux pairs of the break points are punched in fields CUR and FLUX (columns 1-32), one pair of values per card.

c) The order of input of the break points must be as follows: the first point specified must be the first point following the negative saturation point, the points are then specified in order, up to and including the first point after the positive saturation point. The next to last point specified must always be the positive saturation point. The negative saturation point is defined from the positive saturation point by symmetry in EMTP.

All points must be strictly montonically increasing in both flux and current.

```
CUR              FLUX
E16.0            E16.0
```

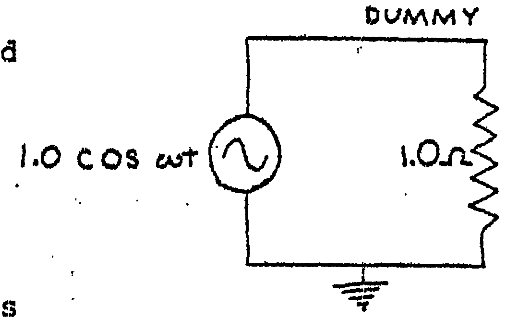
```
                            9999
```

Sample data listing

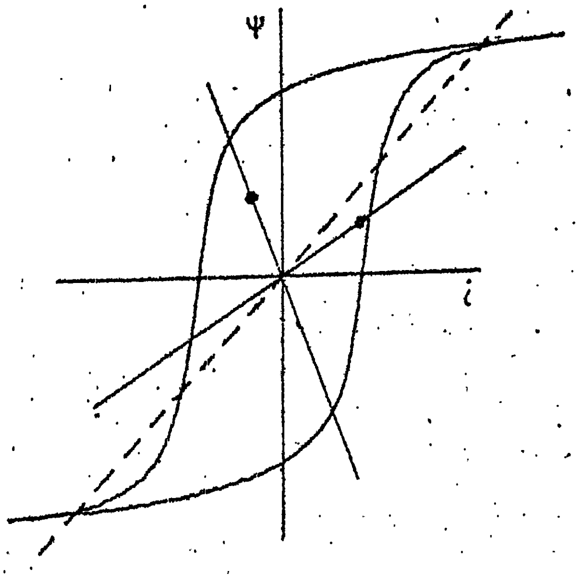
```
96NODEA NODEB                          8888.                0.6
           -0.25             -0.9706
           -0.312            -0.9194
           0.1875            -0.8471
           0.4375            -0.658[illegible]
          0.[illegible]4375          [illegible].5[illegible]06
          0.13125            [illegible].5[illegible]39
           0.225             [illegible].3[illegible]47
        0.4[illegible]            [illegible].9412
                              1.0
         1.375              1.0059
           9999
96NODEC NODED NODEA NODEB 0.1063 .8235                     0.6
```

Important Information concerning Type-96 Usage

Whenever a type-96 element is being used in a run, there must be at least one source connected in the steady-state. The subnetwork containing the type-96 element may or may not be connected in steady state but there must be at least one subnetwork which is connected in steady state. Such a subnetwork can easily be created as shown in the sketch, where the voltage source at node DUMMY is connected during steady-state. Failure to observe this restriction will result in the run being terminated, with an appropriate error message.

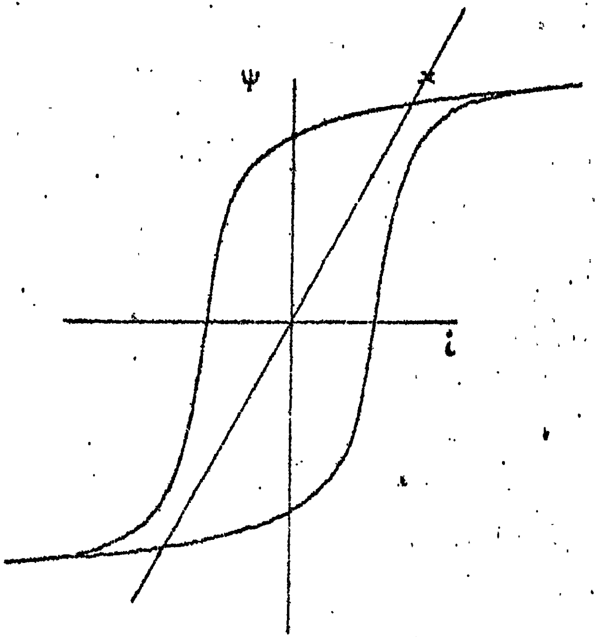


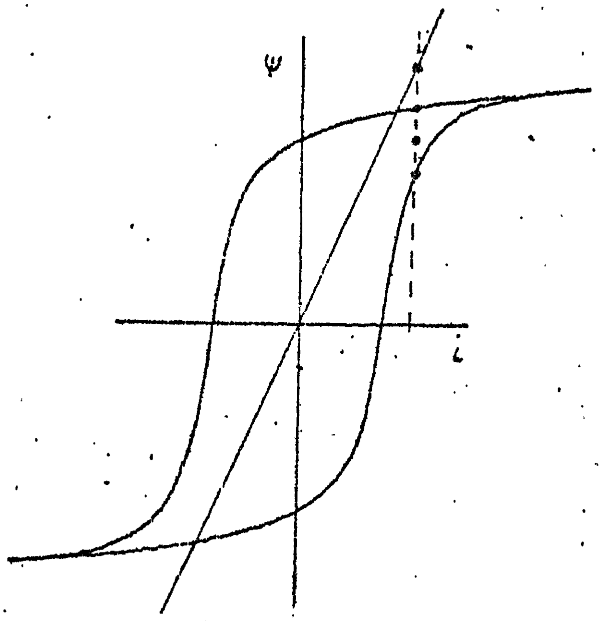
The user should exercise care when he is specifying values of i_{steady} and ψ_{steady}, which are used to define the linear magnetizing inductance ($L = \psi_{steady}/i_{steady}$) that represents the type-96 element during a phasor solution. The only restriction on this point is that it lies within the major loop. As the sketch at right indicates, there are many points that lie within the major loop but yield poor linear representations of the loop. A handy rule of thumb might be to only



pick points in the first quadrant and never pick a point which yields an inductance smaller than the inductance obtained by using the positive saturation point as the stead-state point.

The user should also keep in mind that at time zero, the type-96 will switch from being represented as a linear inductance to being represented by the non-linear, multi-valued hysteresis characteristic (which is then internally represented linearly at each time step). Herein lies a potential problem. If the initial point lies within the major loop there is no problem, operation simply begins at that point and proceeds from there as determined by the system. However if the initial point as determined by a phasor solution lies outside of the major loop, the problem arises because operation outside of the major hysteresis loop cannot occur in a real core. It



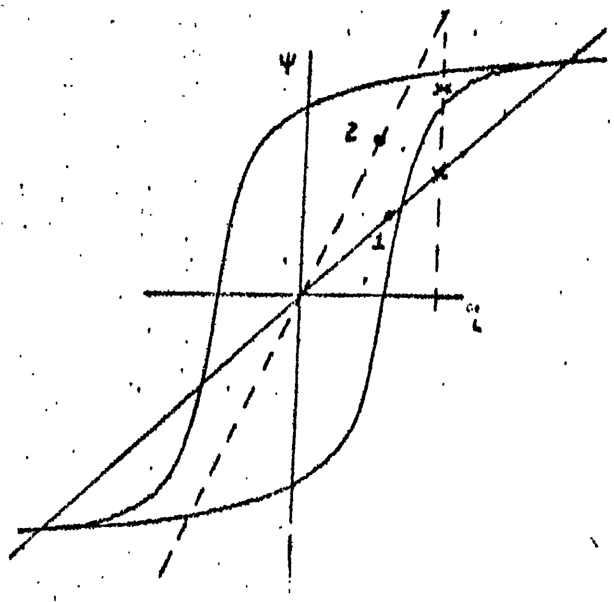


happens here only because of the linear representation used in the steady-state solution. The EMTP therefore will move the initial point within the major loop (rather than terminating the run at this point, which is the only other option available). The scheme for moving the initial point into the major loop is as follows: draw a line of constant current through the initial point, determine the two points where it intersects the top and bottom half of the major loop (these will be the same points if $i(o) \geq i_{\text{positive saturation}}$ or $i(o) \leq i_{\text{negative saturation}}$) and take the average of these two points as the new initial point. Whenever this happens the following message is printed:

```
NOTE ---- NONLINEAR ELEMENT NUMBER  I4 IS A TYPE-96 HYSTERETIC INDUCTOR WHICH IS CONNECTED
          BETWEEN BUSSES  ' A6 '  AND  ' A6 ' .   THE INITIAL FLUX-CURRENT POINT AS FOUND BY THE
          PHASOR STEADY-STATE SOLUTION HAS BEEN OBSERVED TO LIE OUTSIDE THE USER-DEFINED MAJOR HYSTERESIS LOOP, HOWEVER.
          THE INITIAL FLUX IS      E14.4    AND THE INITIAL CURRENT IS   E14.4   .   THE EMTP SHALL NOW ALTER THIS
          JUST-PRINTED FLUX SO AS TO MAKE IT LEGAL, WHILE HOLDING THE CURRENT CONSTANT.   THE LINE OF CONSTANT CURRENT
          INTERSECTS THE USER-SUPPLIED MAJOR HYSTERESIS LOOP AT TWO POINTS (POSSIBLY EQUAL, IF THE CURRENT IS LARGE
          ENOUGH).   THE  'UPPER'  IS CUT AT FLUX VALUE    E14.5    ,   AND THE  'LOWER'  AT FLUX VALUE    E14.5  .
          THE INITIAL FLUX SHALL BE TAKEN BY THE EMTP TO BE THE AVERAGE OF THESE, WHICH HAS FLUX VALUE    E15.5   .
```

It is the user's responsibility to determine if the change made is acceptable or not. It should be realized that transients due to sudden changes in flux (like those being made here) may die out very slowly. It is strongly suggested that the user make legitimate alterations which cause all such messages to disappear.

One potential cause for this type of problem could be a poor choice of i_{steady} and ψ_{steady} as discussed above. Consider the example in which a relatively low value of inductance (by means of point 1) was chosen to represent the loop during the phasor solution. Notice the required change in flux as discussed above. If point 2 is used as the steady-state point rather than point 1,



it is quite likely that no such problem with initial point outside of the major loop will occur. Any time the EMTP creates a new initial point whose flux coordinate is larger (in absolute value) than the intial point originally calculated from the phasor solution, one should check for the situation discussed in this example.

It should also be noted that for balanced 3-phase initial conditions, the user can always shift his time reference (rotate the phase angles of all sinusoidal sources by some fixed phase angle) so that none of the three initial fluxes exceeds $\sqrt{3}/2 \approx .866$ times its peak value. In terms of figures which can be read from the phasor steady-state solution printout of branch flows, this corresponds to shifting the time origin so that current in one of the three components (for the 3-phase representation) is exactly zero at time zero.

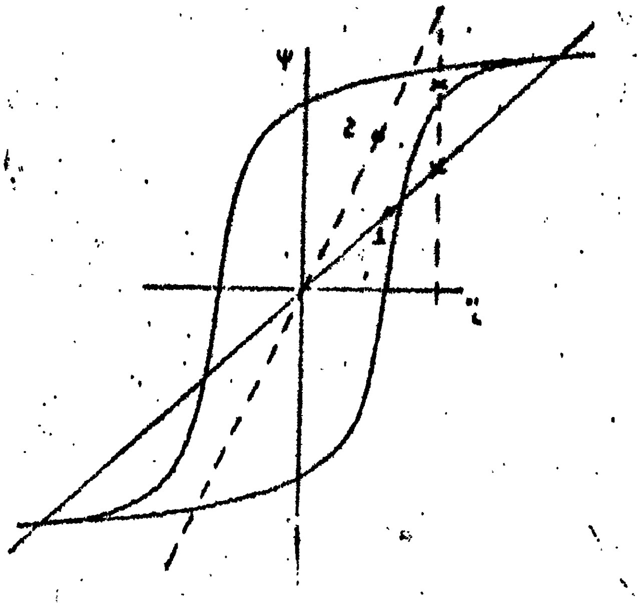
If steps such as these do not eliminate problems of initial points outside of the major hysteresis loop, the user must decide if the changes made by EMTP are of small enough magnitude to be accepted or not.

The intelligent user will learn to always check the initial flux in each type-96 element in addition to checking for the happens here only because of the linear representation used in the steady-state solution. The EMTP therefore will move the initial point within the major loop (rather than terminating the run at this point, which is the only other option available). The scheme for moving the initial point into the major loop is as follows: draw a line of constant current through the initial point, determine the two points where it intersects the top and bottom half of the major loop (these will be the same points if $i(o) \geq i_{\text{positive saturation}}$ or $i(o) \leq i_{\text{negative saturation}}$) and take the average of these two points as the new initial point. Whenever this happens the following message is printed:

```
NOTE ---- NONLINEAR ELEMENT NUMBER I4 IS A TYPE-96 HYSTERETIC INDUCTOR WHICH IS CONNECTED
          BETWEEN BUSSES ' A6 ' AND ' A6 '.  THE INITIAL FLUX-CURRENT POINT AS FOUND BY THE
          PHASOR STEADY-STATE SOLUTION HAS BEEN OBSERVED TO LIE OUTSIDE THE USER-DEFINED MAJOR HYSTERESIS LOOP, HOWEVER.
          THE INITIAL FLUX IS     E14.4   AND THE INITIAL CURRENT IS    E14.4   .   THE EMTP SHALL NOW ALTER THIS
          JUST-PRINTED FLUX SO AS TO MAKE IT LEGAL, WHILE HOLDING THE CURRENT CONSTANT.   THE LINE OF CONSTANT CURRENT
          INTERSECTS THE USER-SUPPLIED MAJOR HYSTERESIS LOOP AT TWO POINTS (POSSIBLY EQUAL, IF THE CURRENT IS LARGE
          ENOUGH).   THE 'UPPER' IS CUT AT FLUX VALUE    E14.5  ,   AND THE 'LOWER' AT FLUX VALUE    E14.5 .
          THE INITIAL FLUX SHALL BE TAKEN BY THE EMTP TO BE THE AVERAGE OF THESE, WHICH HAS FLUX VALUE    E15.5  .
```

It is the user's responsibility to determine if the change made is acceptable or not. It should be realized that transients due to sudden changes in flux (like those being made here) may die out very slowly. It is *strongly* suggested that the user make legitimate alterations which cause all such messages to disappear

One potential cause for this type of problem could be a poor choice of i_{steady} and ψ_{steady} as discussed above. Consider the example in which a relatively low value of inductance (by means of point 1) was chosen to represent the loop during the phasor solution. Notice the required change in flux as discussed above. If point 2 is used as the steady-state point rather than point 1,



it is quit likely that no such problem with initial point outside of the major loop will occur. Any time the EMTP creates a new initial point whose flux coordinate is larger (in absolute value) than the intial point originally calculated from the phasor solution, one should check for the situation discussed in this example.

It should also be noted that for balanced 3-phase initial conditions, the user can always shift his time reference (rotate the phase angles of all sinusoidal sources by some fixed phase angle) so that none of the three initial fluxes exceeds $\sqrt{3}/2 = .866$ times its peak value. In terms of figures which can be read from the phasor steady-state solution printout of branch flows, this corresponds to shifting the time origin so that current in one of the three components (for the 3-phase representation) is exactly zero at time zero.

If steps such as these do not eliminate problems of initial points outside of the major hysteresis loop, the user must decide if the changes made by EMTP are of small enough magnitude to be accepted or not.

The intelligent user will learn to always check the initial flux in each type-96 element in addition to checking for the message discussed above. The initial flux in all nonlinear or psuedo-nonlinear coils, is printed out after the complete steady-state solution, and before the time-step-loop column headings, with a sample being:

INITIAL FLUX IN COIL 'NODEVA' TO 'NODEVB' = E13.5

By checking this, the user will be able to verify that he/she is correctly starting at a specified value of residual flux as desired. One will also be able to determine if the execution inadvertenly begins at the user specified value of residual flux when, in fact, the user wants the initial flux to be calculated from a steady-state phasor solution.

It is anticipated that the user may have some difficulty obtaining the hysteresis characteristics required by the type-96 element. See Section 7.2a for EMTP's attempt at alleviating this difficulty.

1.32 MULTIPHASE ZnO SURGE ARRESTER MODEL

The model of this section provides for true (as opposed to pseudo) nonlinear representation of an arbitary number of ZnO surge arresters. Theory has been documented in Ref. 22, Vol. 1, No. 2 (Dr. W. Scott Meyer) and No. 3 (Dr. Vladimir Brandwajn). The model is compensation-based, and Newton's method is used for iteration to the exact solution at each time step. While it is possible that no solution will so be found (in which case an EMTP error message will result), if the case runs to completion, the answer is correct. Uncertainty associated with pseudo-nonlinear elements like the Type-99 resistor thus has been removed.

The basic constraint equation is resistive, and highly nonlinear:

i = p * (v / Vref)**q (1)

Typically one picks the reference voltage Vref to be rated voltage, or something close to it. In theory, the choice is arbitrary (it is an extra parameter). This then normalizes the equation, and prevents numerical overflow. Then constants "p" and "q" are unique characteristics of the device. Typical 1980 ZnO designs have "q" near thirty.

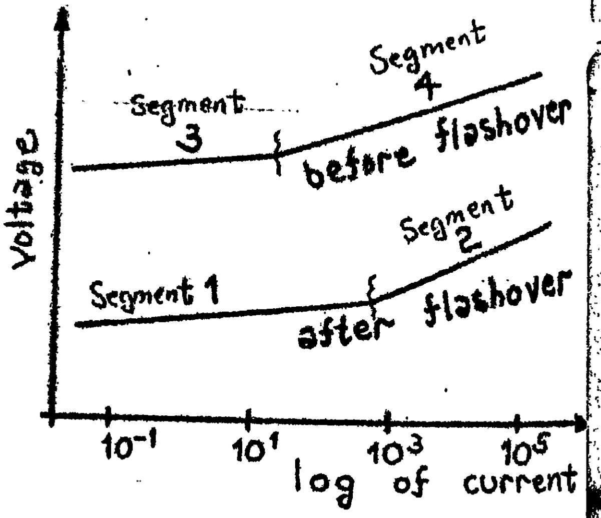
Nonlinearity for q=30

i/p	.0012	.0424	1.0	17.45	237.4	2620	24201
v/Vref	0.8	0.9	1.0	1.1	1.2	1.3	1.4

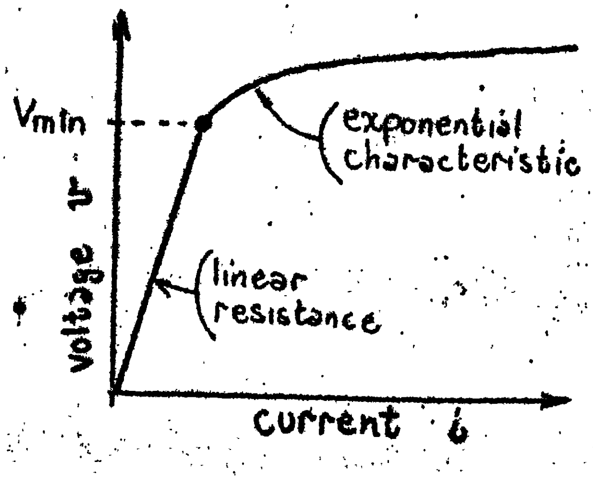
But there is an additional flexibility which allows for gaps, and also different constants for different current ranges of the operation. As of May 1980, exactly two sets of constants for each of two characteristics are allowed for each arrester. This is shown at the right, where different segments of the characteristics are numbered one through four. We have:

1 : low current, after flashover;
2 : high current, after flashover;
3 : low current, before flashover;
4 : high current, before flashover.

This same numbering will be used for data input.



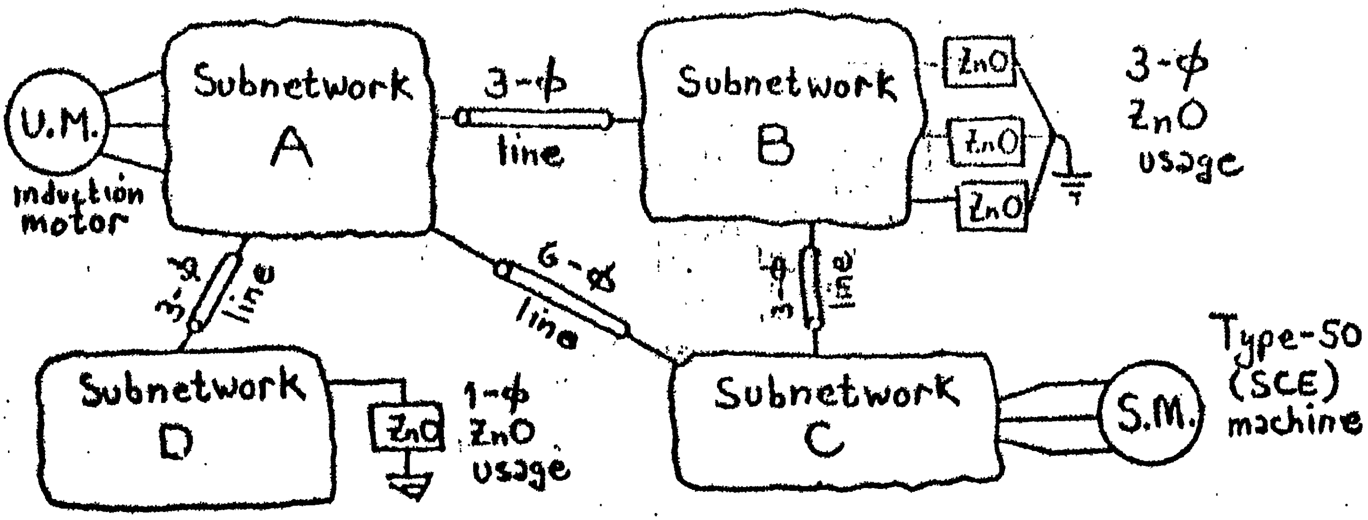
A final deviation from the simple exponential model concerns operation at low voltage. Due to the extreme nonlinearity of ZnO characteristics, very little current is drawn for voltages that are substantially below rated voltage Vref (e.g., 0.5**30 = 9.E-10). So as to avoid the possibility of exponentiation underflow, and also to speed the solution, linear



representation is actually used for low voltages (see sketch). But this is sort of hidden, and need not concern the user. In physical terms, the solution is unaffected by this usage (no ammeter could detect the difference).

Data cards for this component can be generated automatically by the support routine "ARRDAT" (mnemonically, "arrester data"). This is described in Section 7.2b, and is reached by key word "SATURATION" followed by key value FREQ = 77 . Least mean square fitting is used.

The use of multiphase compensation has some limitations which should be clearly understood. The most common application is for a 3-phase connection of arresters, using 3-phase compensation. The EMTP will normlly be dimensioned to handle this (see List 24 , Section 0.6). Such arresters are associated with a subnetwork which is then isolated (disconnected mathematically) from other such subnetworks by distributed-parameter transmission lines. No other compensation-based components can belong to the same subnetwork as the ZnO arresters. Thus, a subnetwork which uses the universal machine (U.M.; also compensation-based) can not involve the present ZnO arrester modeling, and vice-versa. In some cases a six-phase grouping of arresters can profitably be used, when both the high and the low sides of a 3-phase transformer bank are protected, and one does not want to worry about introducing stub lines to isolate the two sides (as described in Section 1.3). But the user should approach such larger groupings with caution, since the convergence of Newton's method may be adversely affected.



Finally, there is some application of the present model to silicon carbide (SiC) arresters, though serious (perhaps unacceptable) approximations must be made. No dynamics of the gap can be provided, unlike the sophisticated single-phase model of Section 1.34 . Hence the possibilities of such usage shall not be emphasized here. Consult Vladimir's discussion in Vol. 1, No. 3 of the Newsletter for further details In essence, one is representing the block very accurately ("two exponential segments appear to provide a very adequate fit"), and ignoring totally the dynamics of the gap (after flashover). But if one can not get data for the Type-94 representation of Section 1.34, maybe this is the best we can do for the time being.

A. Data Formats for ZnO Surge Arrester Representation

Development of ZnO surge arrester modeling in the EMTP is not yet in its final production state, and data requirements are still a little cumbersome. Indeed, data cards associated with any one ZnO arrester are split, appearing at two different points in the input data stream. Along with EMTP branch cards must be the appearance of a Type-92 element which bears a special ZnO flag. This is the first half of the split data. The second is to come immediately before the request for node voltage outputs, where the ZnO characteristic is actually defined. Details follow, and Section B shows an example.

1. EMTP branch cards for ZnO arresters

						80
92	A6	A6	A6	A6	5555.	I2
	BUS1	BUS2	BUS3	BUS4		IOUT

Here we are using a special modification of the Type-92 non-linear element format, as illustrated at the right. Data fields "BUS1" and "BUS2" are for the arrester terminal node names, as usual. Columns 27-32 are to be punched with the special flag "5555." as a marker for ZnO usage. The column-80 branch output requests are as usual (variable "IOUT"). As for reference-branch name fields "BUS3" and "BUS4", these may be used only for the second and later such ZnO arresters, in order to avoid the input of (i, v) data points of the Type-92 characteristic. But the first such Type-92 ZnO branch card must be followed by a dummy characteristic (the three cards shown at the right suffice).

current	voltage
-1.0	-1.0
1.0	1.0
9999.	

2. Data cards for ZnO characteristic (the real one)

Immediately before the first data card which specifies node voltage outputs (Point 8 of the Section 1. data classification), must come data cards which give the voltage vs. current characteristics of all ZnO arresters. There will be one such specification for each of the special Type-92 ZnO specifications just described. Ordering of the characteristics must correspond exactly to the input ordering of the associated Type-92 branch cards. As for the exact form of the characteristic data, there are two different situations:

a) Single exponential, no gap

If the user is satisfied with just a single exponential, and if he desires no gap, then a single data card suffices for specification of such a segment:

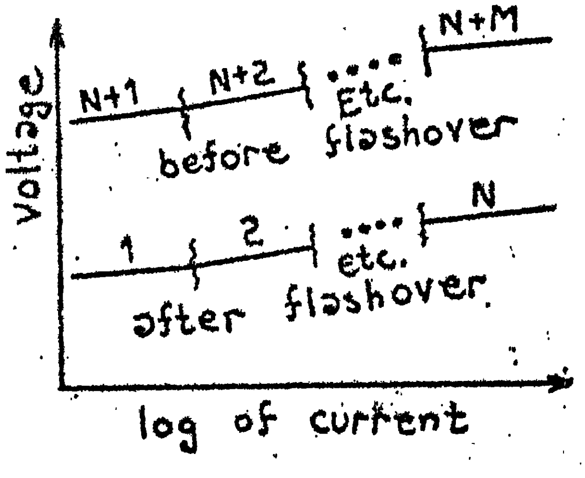
I8	E16.0	E16.0	E16.0	E16.0	E8.0
IPHASE	ZNOCON	ZNOEXP	ZNVMIN	VOLOLD	ZNVREF

IPHASE ---- (1-8)	The negative of the phase number (1, 2, etc.) of the multi-phase compensation which is to be used for this element. Thus all uncoupled elements are to have a "-1" punch, corresponding to phase "a" . For a three-phase configuration, the first element is to have value "-1" , the second one "-2" , and the third "-3" . Etc. for other cases. Do not forget the minus sign, which is a special flag indicating a single exponential without any gap.
ZNOCON ---- (9-24)	Coefficient "p" of the ZnO constraint equation i = p * (v/Vref)**q .
ZNOEXP ---- (25-40)	Exponent "q" of the ZnO constraint equation i = p * (v/Vref)**q .
ZNVMIN ---- (41-56)	Minimum voltage for usage of the just-stated characteristic, in per unit (as a fraction of variable "ZNVREF" which is described immediately below). Below this voltage level, a linear resistance is used.
VOLOLD ---- (57-72)	Arrester voltage from the previous time step. Leave blank (zero) in almost all cases. The Newton iteration will then start with zero current (arrester open).
ZNVREF ---- (73-80)	Reference voltage "Vref" of the ZnO constraint equation i = p * (v/Vref)**q . If the same as for the preceding arrester, zero or blank can be punched.

b) multi-exponential, gapped case

On the other hand, if one or more arresters requires a gap, or if it requires more than one exponential for accurate representation, then a number of data cards are required to describe the characteristic. However, the user does not typically punch these himself. Instead, he executes the supporting routine "ARRDAT" of Section 7.2b, and then saves the punched-card output (from I/O channel LUNIT7) for this use.

As a summary of the data requirements, the following is provided. Specification of the characteristic begins with data cards for the curve after flashover (see sketch at right). There are "N" such segments (an indeterminate number), ended by a "9999" card just as most EMTP characteristics are. Then come data cards for the curve before flashover. It is assumed that there are "M" such segments (an indeterminate number), ended by a "9999" card. All such segment cards begin with the same three data fields as shown in the format at the right. The meaning of these variables is:



I8	E16.0	E16.0
IPHASE	COEF	EXPON

IPHASE (1-8)	----	Phase number (1, 2, etc.) of the multi-phase compensation which is to be used for this element. All uncoupled elements are to use unity, which corresponds to phase "a" . For a 3-phase configuration, the first element is to have value unity, the second value two, and the third value three. Etc. for other cases.
COEF (9-24)	----	The coefficient "p" of the Zno constraint equation i = p * (v/Vref)**q for the segment.
EXPON (25-40)	----	The exponent "q" of the ZnO constraint equation i = p * (v/Vref)**q for the segment.

The ordering of these different segment cards must correspond to the preceding sketch: for each of the two curves, they begin at low current, and end at the highest current. As mentioned before, the lower impedance curve (after flashover) must precede the higher impedance one (before flashover).

Not explained in the uniform explanation of the preceding text is the use of two voltage fields (each E16.0 format) that lie to the right of "EXPON" . These are "VOLT1" and "VOLT2" as shown in the format at the right. The usage and meaning vary, from segment to segment:

E16.0	E16.0
VOLT1	VOLT2

a) For segments 1 and N+1, "VOLT1" is the minimum voltage for use of exponential modeling, in per unit based on reference voltage Vref . At lower voltage, a linear resistor is used.

b) For segment one, "VOLT2" is the arrester voltage from the previous time step. Leave blank (or zero) in almost all cases. The Newton iteration will then start with zero current.

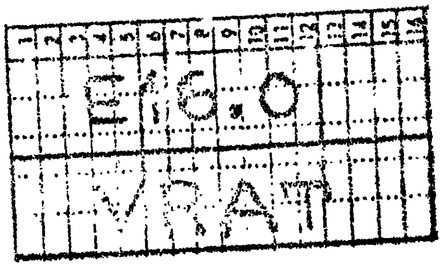
c) For segment N+M , "VOLT2" is the arrester flashover voltage, in per unit using Vref as the base voltage. After this voltage is exceeded, operation switches from the high-impedance curve to the low-impedance curve.

d) For segments other than 1 or N+1 , "VOLT1" is the beginnin voltage (the lowest voltage) of the segment. This value defines the lower limit for the segment in question.

****
RESTRICTION : As of the "M28." code of September, 1980, this
************ ZnO arrester modeling is restricted to the case M = N = 2 . That is, both the low impedance (after flashover) and high-impedance (before flashover) characteristics must consist of exactly two segments each. Later, we plan to generalize the input to allow for an arbitrary number of segments. But for now, there must be two for each curve.

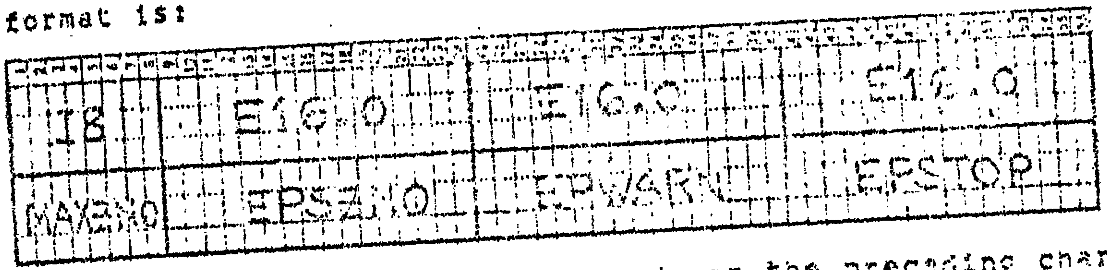
Also missing from the previous uniform explanation is the existance of a voltage-rating data card, which immediately follows the final (second) 9999-card of the characteristic:

VRAT ---- Arrester rating in volts. Inside the EMTP, this value will be doubled, to give the reference Vref of the voltage constraint equation i = p * (v/Vref)**q



3. Single data card controlling Newton iteration

After the final data card of Point 2 above, there is to be a single data card that is punched with constants related to the overall usage (particularly the Newton iteration procedure). The format is:



No blank card terminates this card, or the preceding characteristic cards; the EMTP knows how many arresters (if any) a data case has, and simply reads the appropriate data cards. As for the meaning of constants on this final ZnO data card, we have:

MAXZNO ---- (1-8) Maximum number of Newton iterations which will be allowed for the solution of the surge arresters in each subnetwork. The Newton iteration will go this long unless tolerance EPSZNO is attained first.

EPSZNO ---- (9-24) Convergence tolerance for the Newton iteration. All voltage corrections of the coupled elements must be smaller than this in absolute value for the equations to be judged solved. A blank (zero) value is taken as a request for the value EPSILN * Vref, where EPSILN is the familiar floating-point miscellaneous data parameter of Section 1.0h (1.E-8 for 60 and 64-bit versions like CDC, IBM, PRIME, VAX, SEL).

EPWARN ---- (25-40) Voltage convergence tolerance for non-fatal warning message about a "sloppy solution." A blank (zero) data field is taken as a request for the value Vref / 1000 ---- representing one tenth of one percent of rated voltage, then, which is about the limit of graphical resolution.

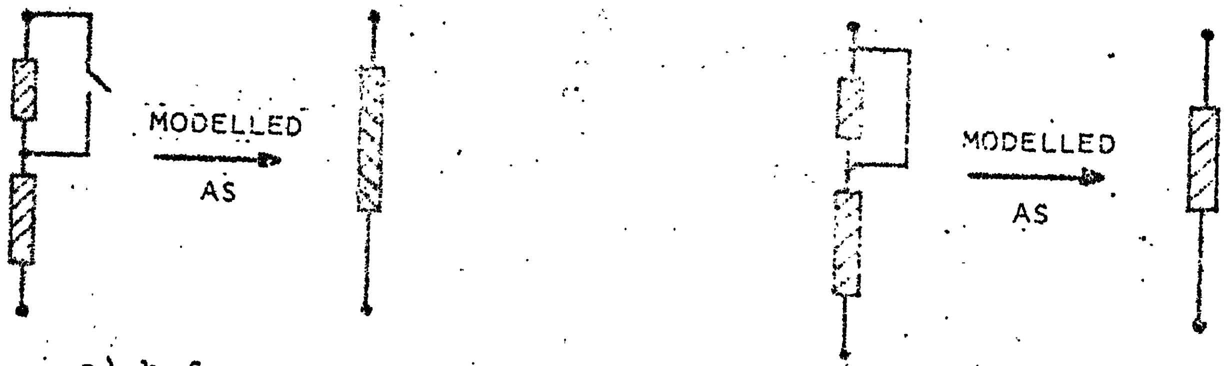
EPSTOP ---- Voltage convergence tolerance for a fatal error stop
(41-56) complaining about a non-converged iteration. A blank (zero) data field is taken as a request for the value Vref / 10 ---- or 10% of rated voltage. The current error in such a case could be astronomical, remember, due to the extreme nonlinearity (e.g., 1.1**26 = 11.9)

B. Use of Gaps for Practical Arrester Applications

The following material has been extracted from Vladimir's "User's Instructions for the EMTP Representation of ZnO Surge Arresters," dated 8 April 1980 . This material was printed by Ontario Hydro, and provides insight into use of gap modeling.

At any point of time, the arrester is represented by a block with a variable conductivity (resistance). The value of this conductivity varies as the operating point of the arrester changes. The variation may be smooth or discontinuous. Consider, for example, an arrester equipped with a shunt, passive gap shown in Figure 1.
Similar diagrams can be drawn for an arrester with a series passive gap, with the gap represented as a very high resistance.

The protective characteristic of an arrester is divided into 3 regions. The parameters for only two of the regions are specified on the data cards. The parameters for the third region, the leakage current region, are derived automatically by the program as a linear resistance. The three segment representation is used to represent arrester before gap sparkover as well as after the sparkover. Consequently, four sets of parameters have to be specified for each arrester even if a gap is not modelled.



a) before sparkover

b) after sparkover

Figure 1. Representation of an arrester with a shunt gap.

Consider, once more, an arrester equipped with a shunt gap. Its idealized voltage-current characteristic is shown in Figure The numbers in circles correspond to the numbering sequence of the segments within the program. They also correspond to the data input order.

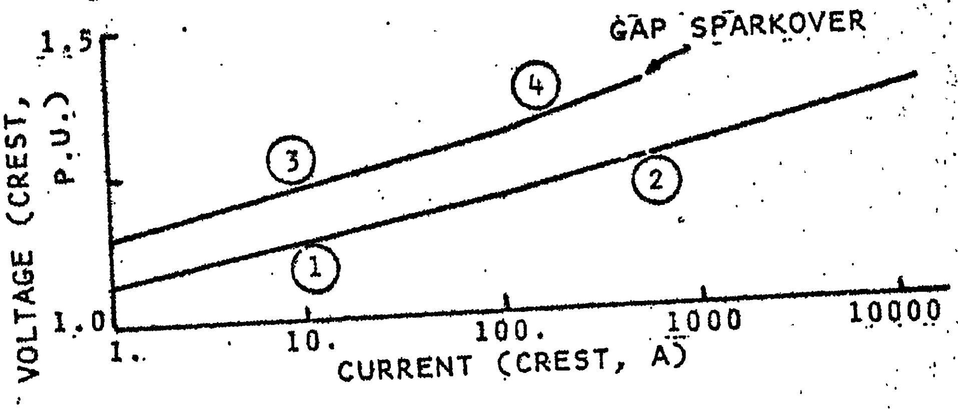


Figure 2. Protective characteristic of an arrester with a shunt gap.

5.0 Hints about the modelling of gapped and ungapped arresters

A number of different data combinations are possible due to the multiplicity of designs represented by the new model. These combinations are discussed briefly below.

5.1 Arresters with shunt gaps

The data cards discussed in section 4, describe an arrester with a shunt gap. The arrester characteristic, before gap sparkover as well as after it, contains two exponential segments. Segments #1 and #2 describe the characteristic after sparkover and segments #3 and #4 before sparkover. If the user wants to specify a characteristic with one exponential only, he should specify the voltage VMIN for the second segment as equal to that of the first one. The other parameters can be left blank (zero).

5.2 Gapless arresters

In order to specify a gapless arrester, make the cards for segments #1 and #2 identical to those for #3 and #4. Specify the voltage VMAX (col. 57-62 of data card for segment #4) as a large number, for example 10.0.
Modelling of single exponential characteristic is done as described in point 5.1.

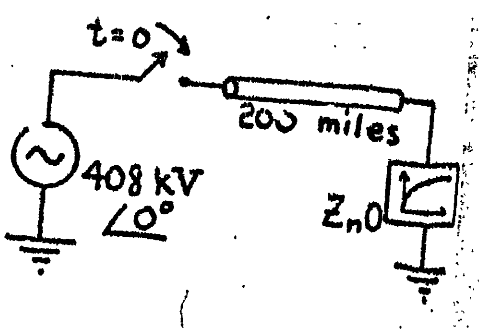
5.3 Arrester with series gaps

Once more, the characteristic of the gap is described by segments #3 and #4, and that of the ZnO block by segments #1 and #2.

The gap, when open, permits the flow of a very small leakage current. This behaviour can be modelled by either a linear or nonlinear (exponential) resistor. Remember, a linear segment has an exponent a = 1.0.

Good results have been obtained with a linear resistor of $10^8 - 10^9$, Remember, the program uses admittance formulation and the gap characteristic is to be specified accordingly.

C. Sample ZnO Data Structures



As a first example, consider the gapless, single-phase example of issue No. 2 of Ref. 22. The schematic is as shown at the right, with just a single exponential used to represent the ZnO arrester characteristic:

p=2500 amps   q=26   Vref=778 kV

A listing of the data case follows:

```
BEGIN NEW DATA CASE
 .000050 .020000
       1       1       1       0       1      -1       0       1
       2      10      33       1      40      10     100      50
-1SEND  REC                 .306  5.82  .012  200.
92REC                      5555.
             -1.             -1.
              1.              1.
           9999.
BLANK CARD ENDING BRANCH DATA.
BLANK CARD ENDING SWITCH DATA.
14SEND       408000.      60.
BLANK CARD ENDING SOURCE CARDS.
      -1            2500.             26.              0.5
      20          778000.
1
  PRINTER PLOT
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
 144 4. 0.0 20.         REC
BLANK CARD ENDING PLOT CARDS.
BEGIN NEW DATA CASE
```

If a gap and/or two exponentials were used in the modeling, then only the card immediately after the blank card ending source cards would change; it would be replaced by six cards, such as:

```
1           2500.             26.             0.5
1                                             0.5
     9999
1           2500.             26.             0.5
1                                             0.5             10.
     9999
```

This is not a realistic application. In fact, it gives identical results to the single card that was replaced, since the gap will never flash over (VOLT2 = 10 per unit), and operation is artificially constrained (note equality of all VOLT1) to the single first exponential (this is one of Vladimir's tricks). But this example does show the structure of the general case.

As for a 3-phase example, again consider the gapless, single-exponential case of issue No. 2 of Ref. 22:

```
-1SENDA RECA
-2SENDB RECB              .305515.8187.01210  200.  0
-3SENDC RECC              .031991.5559.01937  200.  0
92RECA                     5555.
             -1.              -1.
              1.               1.
           9999.               
92RECB        RECA         5555.
92RECC        RECA         5555.
BLANK CARD ENDING BRANCH DATA.
BLANK CARD ENDING SWITCH DATA.
14SENDA      408000.       60.      0.0
14SENDB      408000.       60.     -120.
14SENDC      408000.       60.      120.
BLANK CARD ENDING SOURCE CARDS.
     -1            2500.           26.              0.5
     -2            2500.           26.              0.5
     -3            2500.           26.              0.5
     20          778000.
1
 PRINTER PLOT
```

D. Fixed-Dimension Limits, Singular Matrices

As of September, 1980 ("M28." program versions), the zinc-oxide surge arrester modeling still has dimensioned limits which are fixed. Limits are a maximum of 10 coupled arresters (10 arresters in any one subsystem), and a total of 20 ZnO arresters total. Should the user have need of bigger limits, Program Maintenance can readily alter the FORTRAN to accommodate him. Dimensioned storage appears in modules "TOP15" of overlay 15 and "ZINCOX" of overlay 16. The top of the latter of these appears as follows:

```
       SUBROUTINE ZINCOX ( I )
       INSERT DECK  BLKCOM
       INSERT DECK  LABCOM
C      STORAGE FOR ZINC-OXIDE SURGE ARRESTERS.  DIMENSION
C      VECTORS TO MAXIMUM NUMBER OF COUPLED ELEMENTS.
       COMMON  /ZNO/  ZNOCON(10), ZNOEXP(10), VOLOLD(10)
       COMMON  /ZNO/  VTHEV(10), CURNL(10), FOLD(10)
       COMMON  /ZNO/  ZNVMIN(10), ZNCOND(10)
       COMMON  /ZNO/  KSING(10), KINDEP(10)
C      VECTORS OF  /ZN2/  ARE DIMENSIONED TO MAXIMUM TOTAL
C      NUMBER OF  ZINC-OXIDE ARRESTERS.  SEE ALSO  "TOP15" .
       COMMON  /ZN2/  ZEXP(20),ZSWT(20),ZMUL(20),ZNEXP(20),ZNMAX(20)
       COMMON  /ZN2/  ZNMUL(20),ZNMIN(20),ZOSWT(20),ZOMUL(20),ZOEXP(20)
       COMMON  /ZN2/  ZNSLOP(20),ZNVRF(20)
       DIMENSION MILOC(10),MILOR(10),ZSOL(10)
```

Another aspect of the ZnO implementation which deserves comment is possible singularity of the equations being solved. The solution of each coupled arrester group is performed within "ZINCOX" using the general purpose linear equation solver "DGELG" which came with the SCE (Type-50) S.M. model of Section 1.62b . Pivoting is involved, along with miscellaneous data parameter "EPSILN" to measure possible singularity. Well, there has yet to be found a situation where this tolerance falsely caused trouble, when solutions were proceeding normally. But it is not uncommon for there to be an EMTP error stop (KILL = 209, LSTAT(19) = 3501) if the iteration is diverging. Typically this is the result of excess voltage, which then is fed into the ZnO nonlinearity to produce astronomical currents; the elements of the Jacobian matrix thus are quite abnormal, and it is the singularity test of "DGELG" which terminates the simulation. BPA production users have had this problem in cases where ZnO protection of series capacitors was used, with a fault placed on the system in the phasor sinusoidal steady state solution for initial conditions (Ref. 8, Vol. X, Page MIOG-12, "Rule", 8 March 1980). To save others from the same fate, I reproduce that rule here:

<u>RULE</u> : THOU SHALL NOT BEGIN TRANSIENT SIMULATIONS INVOLVING NEW ZnO SURGE ARRESTER MODELING WITH PHASOR SOLUTIONS WHICH RESULT IN ABNORMAL ARRESTER VOLTAGES.

So, if a run is terminated due to a singular Jacobian, the user is advised to examine the voltages across the arrester at the time of difficulty, since this is the initial guess for Newton's method. Unless such voltages are reasonable physically, the iteration has little hope for convergence. Possibly the iteration limit would simply be reached, but more likely simgularity of the Jacobian would be detected.

1.3 COMMENTS ABOUT BRANCH CARDS FOR NONLINEAR AND TIME-VARYING BRANCHES

A. Number and location of nonlinear and time-varying branches

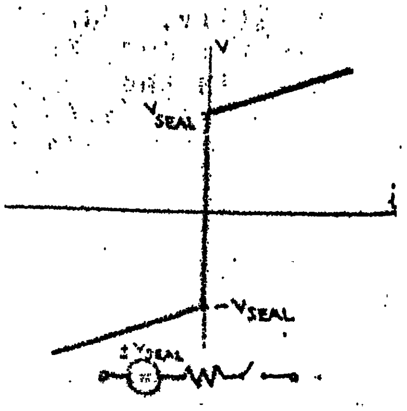
a) Network with only one such branch: No problem arises.

b) Network with more such branches (see also reference 1 and c,d below)

The present solution method assumes that the network has only one nonlinear or time-varying branch within a topologically-connected region. In this respect, it is important to note that branches with distributed parameters do not connect their end nodes topologically (reason: the conditions at one end are seen at the other end not immediately, but only after the elapse of the travel time). Therefore, distributed parameter branches often break the network up into disconnected sub-networks. The solution method will work for more nonlinear or time-varying branches if these are "isolated," that is if each disconnected sub-network has not more than one nonlinear or time-varying branch. This condition can be checked as follows: In the original network graph erase all branches with distributed parameters and also all branches leading to nodes with known voltages (including ground). This will usually result in disconnected sub-networks. Each sub-network must have not more than one nonlinear or time-varying branch. This check is automatically made in the program; if the condition is not met, execution is stopped with the error-message NONLINEAR ELEMENTS AT 'NODE-1' AND 'NODE-2' WITHOUT TRAVEL TIME IN BETWEEN. ' JOB TERMINATED.

Hint for introducing disconnections: A lumped inductance L can be approximated by a lossless line of travel time $\tau = \Delta t$ and surge impedance $Z = \frac{L}{\Delta t}$. Since such a branch with distributed parameters is erased in the connectivity check, it will help in further disconnecting the network. This approximation of a lumped inductance by a short, lossless line is known in the literature as "stub-line representation" (Barthold, L. O., and G. K. Carter, "Digital traveling-wave solutions," AIEE Trans., part III, vol. 80, p. 812, 1961). The stub-line representation must be used with caution; it works only if Z is large compared with the surge impedance of distributed lines (Thorén, H. B., and K. L. Carlsson, "A digital Computer program for the calculation of switching and lightning surges on power systems," IEEE Trans., Vol. PAS-89, pp. 212-218, February 1970).

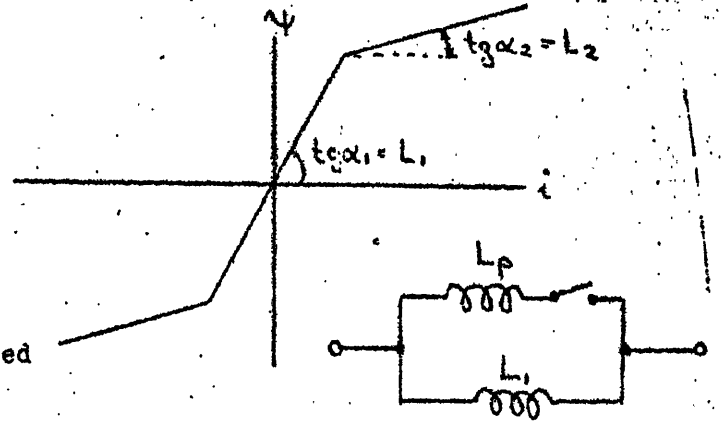
c) Switched resistance (lightning arrester):



A nonlinear resistance with a characteristic of only 2 slopes, one infinite and one finite, can be represented as a resistance in series with a voltage source, the polarity of which changes whenever the sign of the current changes. The series circuit is switched out whenever $|V| < V_{SEAL}$ and switched in otherwise. This "switched resistance" avoids the difficulties associated with nonlinear branches; it is read in as a special switch (see section 1.51). More than 2 slopes can be represented by connecting switched and normal resistances in parallel. The switched resistance is primarily used to simulate lightning arresters as described in section 1.51.

d) Switched Inductance:

A nonlinear inductance with only two different values L_1 and L_2 (nonlinear characteristic with only two slopes) can be represented as two linear inductances in parallel. L_p is switched out when $L = L_1$ and switched in when $L = L_2$. This "switched inductance" avoids the difficulties associated with nonlinear branches; it is read in as a special switch (see section 1.51). More than 2 slopes can be represented by connecting switched inductances in parallel (see section 1.51).



B. Singularity check

Every nonlinear or time-varying branch can have a characteristic with a region where $R \to \infty$ (see Fig.1); therefore, the solution method must account for the eventuality that such a branch is blocked. This blocking might exclude a solution, which will show up mathematically in a matrix singularity. Fig. 2 shows such a case, where no solution exists whenever the nonlinear branch is blocked.

The program does not recognize whether a specific characteristic may or may not block. To make a case with a non-blocking characteristic solvable that would be unsolvable in the blocked state, it is necessary to split the nonlinear branch into two parallel branches--one linear and one nonlinear--, thus providing a branch of finite resistance. This is done by splitting the current in the nonlinear characteristic (see Fig. 3).

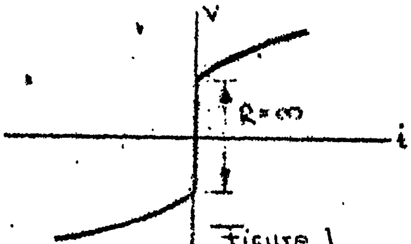


Figure 1.

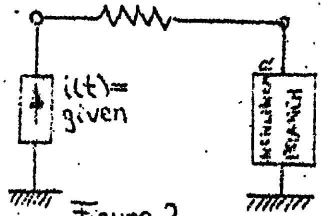


Figure 2.

One branch with potentiality of blocking

Two equivalent parallel branches

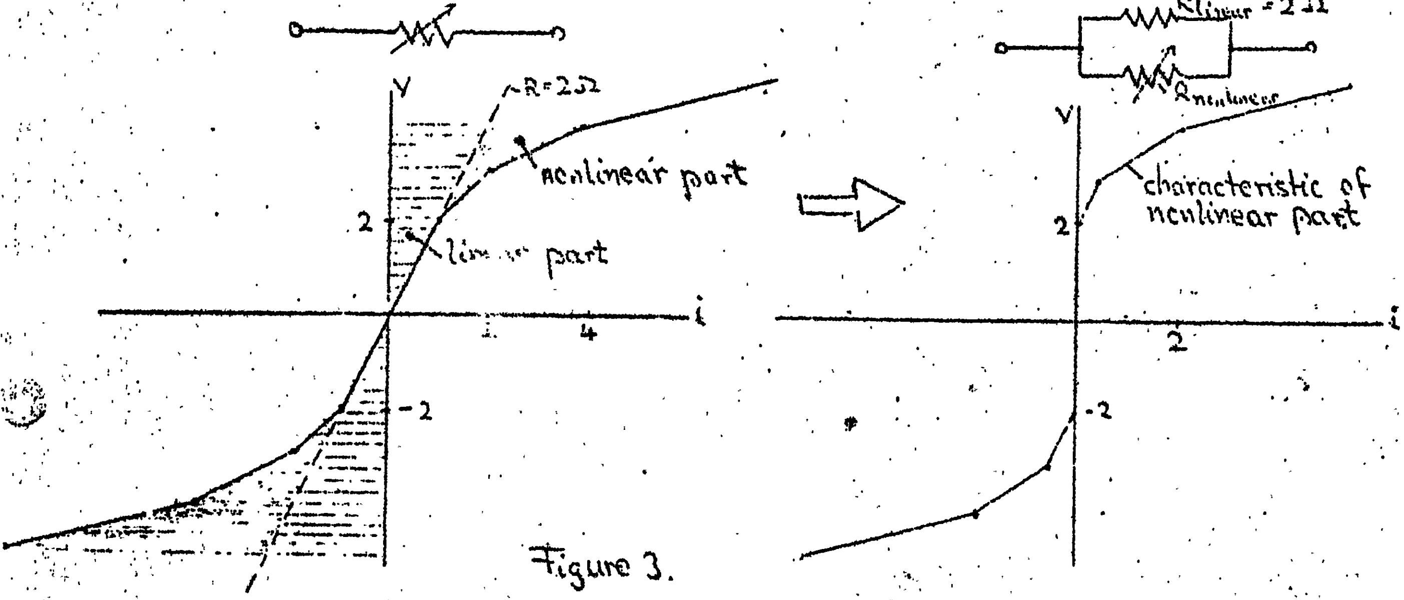


Figure 3.

C. Treatment in steady-state solution to set initial conditions

All nonlinear and time-varying resistances as well as lightning arresters are excluded from the network in the ac steady state solution. Nonlinear inductances are included with their linear region as specified on the branch card (see section 1.37).

D. Network Connectivity Requirement:

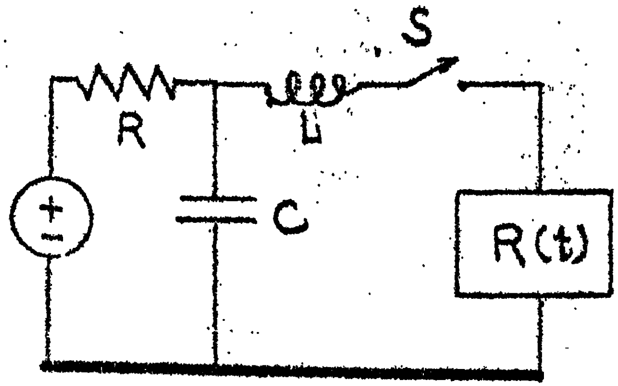
For the Transients Program to be able to solve a problem, the equivalent resistive network of ref. 1 which is solved at each time step must be "connected." That is, one must be able to pass from any one network node to any other network node along network branches of finite resistance. Equivalently, there must be a network path from every node to ground.

Complication

Nonlinear and time-varying elements affect this requirement in that they must be ignored while making the aforementioned connectivity check. No such branch can be used as part of the paths satisfying the connectivity criterion.

Example

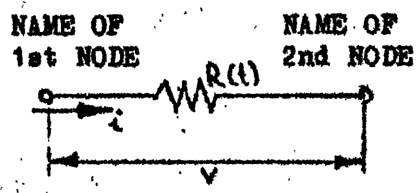
The network sketched at the right can not be solved by the Transients Program in the form shown. With switch S open as shown, ignoration of the time-varying element R(t) leaves the right-hand switch node without a finite-resistance path to ground, and hence disconnected from the rest of the network. This problem would be rejected by the program (the solution process would break down, and the case would be terminated).

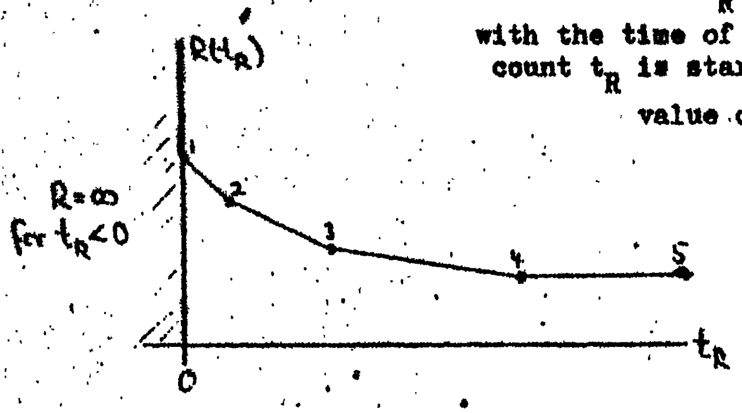


Remedy

One can provide required connectivity by inserting high-resistance paths where needed. By making such a resistance several orders of magnitude larger than other typical problem resistances, the transient solution is unaffected for engineering purposes. But be moderate in selecting such values. One can not in general use arbitrarily large values it has been found. Due to the solution by superposition, one must not make these artificial resistances so large that they are lost in the roundoff of the equivalent diagonal conductances at the adjacent terminal nodes. In terms of floating-point miscellaneous data parameter "EPSILN" , a resistance of 1.E-2 / EPSILN times other representative problem impedances might be reasonable.

1.35 BRANCH CARD FOR TIME-VARYING RESISTANCE





Specify the time-varying resistance $R(t_R)$ point by point as a piecewise linear characteristic (linear interpolation will be used between points). The time count t_R does not have to be identical with the time of the transient study. The time count t_R is started as soon as the absolut value of the voltage v across the blocked branch ($R = \infty$) reaches v_{START} (v_{START} must be specified; if $v_{START} = 0$ then the time count t_R is identical with the time count of the transient study).

CAUTION: It is assumed that $R = \infty$ until $|v| \geq v_{START}$. (Can be changed if desired).

a) RULES

1) Branch type is $\boxed{91}$
2) Specify 2 nodes by names. Nodes may be grounded.
3) The time count t_R for $R(t_R)$ starts as soon as $|v| \geq v_{START}$. Prior to that R is assumed to be infinite.
4) If the characteristic (curve) of the time-varying resistance is identical with that of a preceding branch, then the following storage-saving option may be used:

   Repeat node names of that preceding reference branch in the provided columns 15-26 in the same sequence and also punch v_{START}, but do not add any additional cards for the characteristic.

   CAUTION: Same as in rule 5 of section 1.21.

5) Output options for printing and/or plotting:
   Punch "1" in column 80 to get branch current,
   "2" " to get branch voltage,
   "3" " to get both branch voltage and branch current;
   "4" " to get branch power and energy comsumption (see Section 1.8 for details).

b) **FORMAT and EXAMPLES**

The card with the TYPE number, the node names and v_{START} on it is immediately followed by the cards specifying the characteristic (if option of rul 4 is not used). The characteristic must be specified point by point from left to right (in figure above from point 1 to 5) with one card for each pair f values t_R, $R(t_R)$. Terminate this list by adding a card with 9999 in cols. 13-16.

First card:

	1–2	3–8	9–14	15–20	21–26	27–32	77–80
	BRANCH TYPE	NODE NAMES		NODE NAMES OF REFERENCE BRANCH		V_{START} in units of voltage	OUTPUT OPTION
		BUS1	BUS2	BUS3	BUS4		
FORMAT:	I2	A6	A6	A6	A6	E6.2	I1

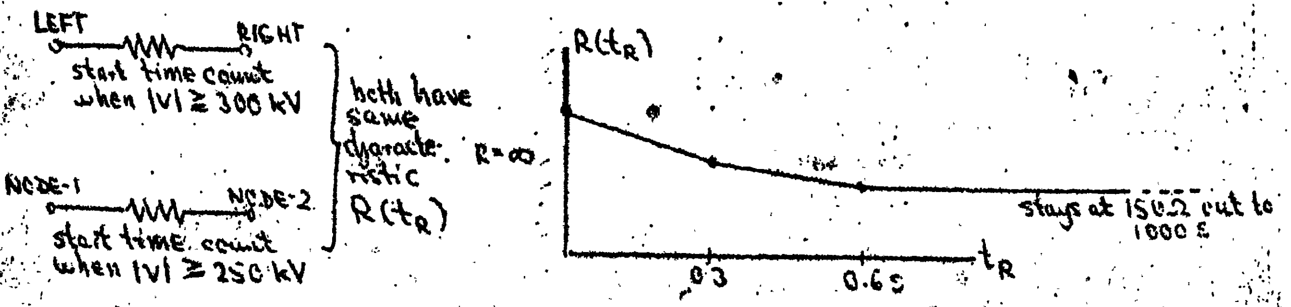
Cards with characteristic:

t_R in sec	$R(t_R)$ in Ω
E16.0	E16.0

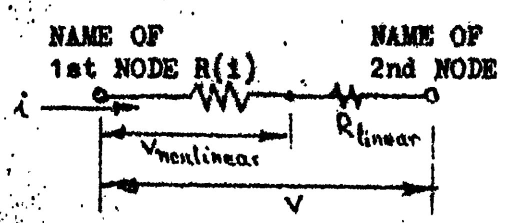
9999

Sample Data Listing

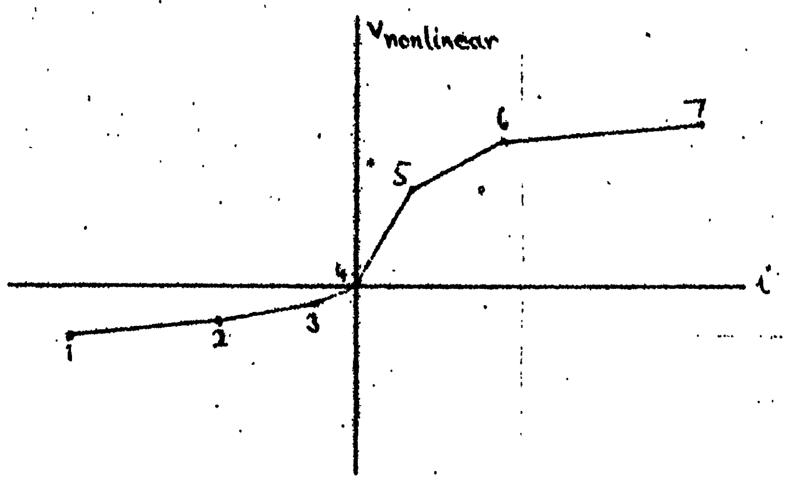
```
91LEFT  RIGHT              0.3E6
             0.0            300.
             0.3            200.
             0.6            150.
           1000.            150.
            9999
91NODE-1NODE-2LEFT  RIGHT   .25E6
```


LEFT
RIGHT
start time count when |V| ≥ 300 kV
NODE-1
NODE-2
start time count when |V| ≥ 250 kV
both have same characteristic R(t_R)
R(t_R)
R=∞
stays at 150Ω out to 1000 s
0.3
0.6 s
t_R

1.36 BRANCH CARD FOR NONLINEAR RESISTANCE, WITH FLASHOVER

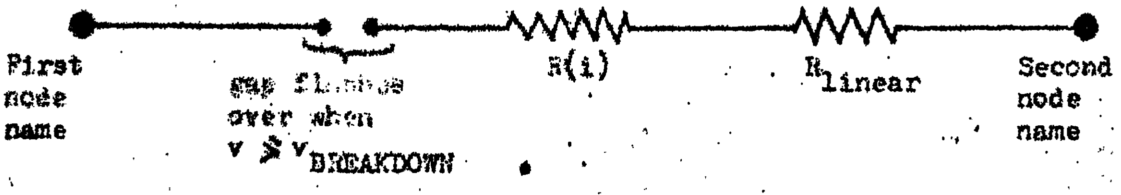


Specify the nonlinear resistance R(i) in series with a linear resistance R_{linear} point by point as a piecewise linear characteristic $v_{nonlinear} = f(i)$ (linear interpolation will b used between points).



Old Style Lightning Arrester: R will be assumed infinite until $|v| \geq v_{BREAKDOWN}$; thereafter $R = R(i) + R_{linear}$ according to specified nonlinear characteristic.

It is assumed that no clearing occurs after discharge (the gap having flashover voltage $v_{BREAKDOWN}$ remains shorted once it has fired). The linear resistance R_{linear} can be used to represent the grounding resistance of the lightning arrester; a value of zero is permissible, if desired.



Nonlinear resistance: Simply omit the gap by setting $v_{BREAKDOWN} = 0$. Also set $R_{linear} = 0$, assuming that all resistance is in the piecewise-linear characteristic.

a) RULES

1) Branch type = $\boxed{92}$.

2) Specify 2 nodes by names. Nodes may be grounded. Positive direction of current is from 1st node to 2nd node.

3) The nonlinear characteristic must be monotonically increasing, that is, the values i, $v_{nonlinear}$ must never decrease when read in from left to right. (If exception from this rule is desired, see Program Maintenance).

4) For a nonlinear resistance set $v_{BREAKDOWN} = 0$. For a lightning arrester, which is an infinite resistance prior to discharge and a nonlinear resistance after discharge, specify the breakdown voltage $v_{BREAKDOWN}$. The program changes from infinite resistance to the nonlinear resistance as soon as $|v|$ reaches $v_{BREAKDOWN}$ and keeps using the nonlinear resistance thereafter. (If $v_{BREAKDOWN}$ is not single-valued but a function of voltage rate of rise or some other criteria, please contact Program Maintenance.

5) If the nonlinear characteristic as well as R_{linear}, are identical with that of a preceding branch, then the following storage-saving option may be used:

> Repeat node names of that preceding reference branch in the provided columns 15-26 in the same sequence and also punch $v_{BREAKDOWN}$ (R_{linear} is ignored), but do not add any additional cards for the nonlinear characteristic.

CAUTION: Same as in rule 5 of section 1.21

6) Output options for printing and/or plotting:
Punch "1" in column 80 to get branch current,
"2" " to get branch voltage,
"3" " to get both branch voltage and branch current;
"4" " to get branch power and energy consumption (see Section 1.8 for details).

7) For a lightning arrester the instance of discharge is printed as LIGHTNING ARRESTER ▨ TO ▨ DISCHARGED AT T = ▨.

b) <u>FORMAT and EXAMPLES</u>

The card with the TYPE number, node names, $V_{BREAKDOWN}$ and R_{linear} on it is immediately followed by the cards specifying the nonlinear characteristic (if option of rule 5 is not used). The nonlinear characteristic must be specified point by point from left to right (in example from point 1 to 7) with <u>one</u> card for <u>each</u> pair of values i, $v_{nonlinear}$. <u>Terminate</u> this list by adding a card with 9999 in col. 13–16.

First card:

	1–2	3–8	9–14	15–20	21–26	27–32	33–38	78–80
	BRANCH TYPE	NODE NAMES		NODE NAMES OF REFERENCE BRANCH		$V_{BREAKDOWN}$ in units of voltage	R_{linear} in Ω	OUTPUT OPTION
		BUS1	BUS2	BUS3	BUS4			
Format:	I2	A6	A6	A6	A6	E6.2	E6.2	I

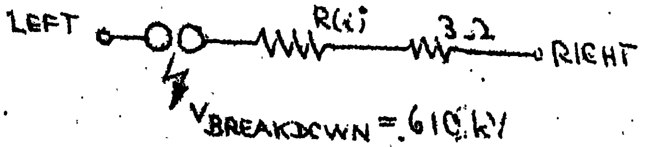
Cards with characteristic:

CUR	VOLT
E16.0	E16.0

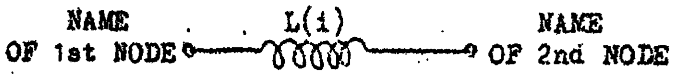
9999

<u>Sample Data Usage</u>

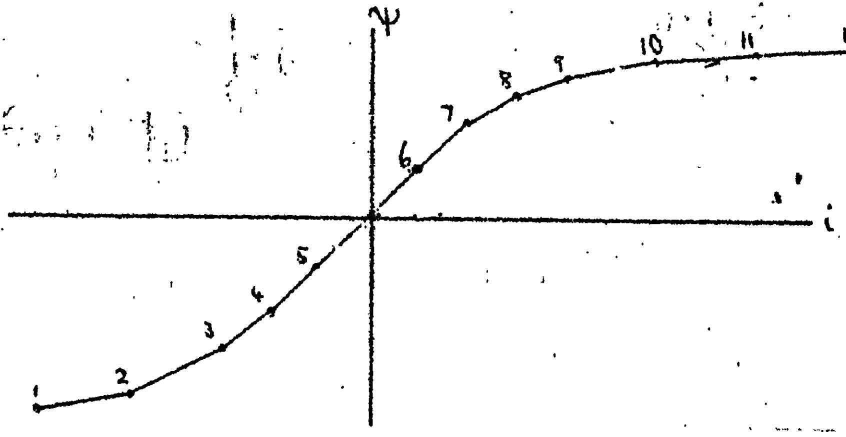
```
92LEFT  RIGHT              .61E6  3.0
        -2.5E3           -580.E3
        -1.0E3           -510.E3
         1.0E3            510.E3
         2.5E3            580.E3
            9999
92ALPHA BETA  LEFT  RIGHT  .55E6
```



1.37 BRANCH CARD FOR NONLINEAR INDUCTANCE



Specify the nonlinear inductance L(i) point by point as a piecewise linear characteristic, $\psi = f(i)$, with ψ = total flux linkage (Linear interpolation will be used between points).



NOTE: $\psi = \psi_{max} \cos\omega t$ for sinusoidal flux with $\psi_{max} = \frac{V_{rms}}{4.44f}$.

A small supporting program exists, which will convert a V_{rms} vs I_{rms} saturation curve into the ψ vs i curve which is needed here, under the assumption that there is no hysteresis. See Section 7.2 for details.

a) RULES

1) Branch type is $\boxed{93}$.

2) Specify 2 nodes by names. Nodes may be grounded. Positive direction of current is from 1st node to 2nd node.

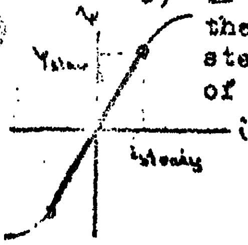
3) The nonlinear characteristic must be monotonically increasing, that is, the values i, ψ must never decrease when read in from left to right.

4) If the nonlinear characteristic (as well as the linear region (explained on next page)), are identical with that of a preceding branch, then the following storage-saving option may be used:

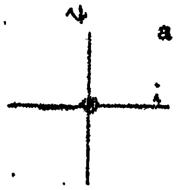
Repeat node names of that preceding reference branch in the provided columns 15-26 in the same sequence and do not add any additional cards for the nonlinear characteristic.

CAUTION: Same as in rule 5 of section 1.21

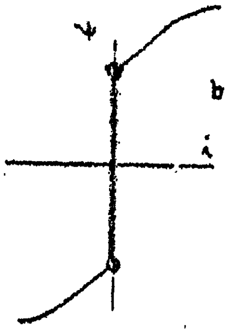
5) Output options for printing and/or plotting:
Punch "1" in column 80 to get branch current,
"2" " to get branch voltage,
"3" " to get both branch voltage and branch current;
"4" " to get branch power and energy consumption (see Section 1,8 for details.



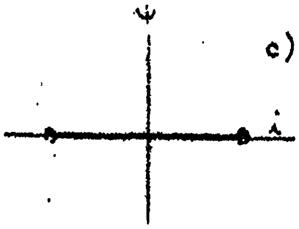
6) If the transients is started from a non-zero ac steady state condition, then the linear region of the nonlinear inductance will be used in the steady state solution. This linear region must be specified as a pair of values i_{steady}, ψ_{steady}. Special cases:



a) $i_{steady} = 0$ or blank
$\psi_{steady} = 0$ or blank
} To be used if no ac steady state solution is asked for or if nonlinear inductances are to be totally ignored during the steady-state solution.



b) $i_{steady} = 0$ or blank
$\psi_{steady} > 0$
} Nonlinear inductance will be non-conducting in steady state solution, but will, in general, have a non-zero initial flux (is computed automatically).



c) $i_{steady} > 0$
$\psi_{steady} = 0$
} Is not permitted (would be a short-circuit in steady state). This case leads to the following error message: "NO INTERSECTION WITH NONLINEAR CHARACTERISTIC NO. ▨ ".

The linear region to be used in the ac steady state solution is defined by the slope $L = \psi_{steady}/i_{steady}$. The initial flux $\psi(0)$ will be listed in the output. If the solution leads to a flux $|\psi(0)| > |\psi_{steady}|$, then the following warning is printed: "*** WARNING. ASSUMPTION THAT AC STEADY STATE HAS FUNDAMENTAL FREQUENCY ONLY IS QUESTIONABLE WITH PRECEDING FLUX OUTSIDE LINEAR REGION."

b) FORMAT and EXAMPLES

The card with the TYPE number and the node names is immediately followed by the cards specifying the nonlinear characteristic (if option of rule 4 is not used). The nonlinear characteristic must be specified point by point from left to right (in figure above from point 1 to 12) with one card for each pair of values i, ψ. Terminate this list by adding a card with 9999 in columns 13-16.

First card:

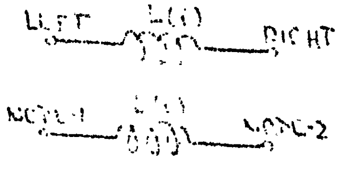
	NODE NAMES		NODE NAMES OF REFERENCE BRANCH		i_{steady} in units of current	ψ_{steady} in units of voltage base s	
	BUS1	BUS2	BUS3	BUS4			OPTION
Format: I2	A6	A6	A6	A6	E6.2	E6.2	I1

Cards with characteristic:

CUR	FLUX
E16.0	E16.0

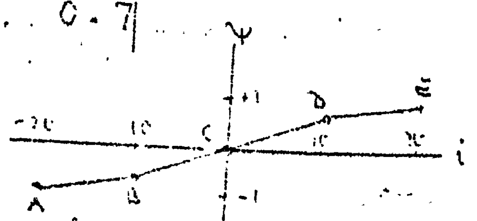
```
            9999
```

Sample Data Usage



} both have same characteristic

```
93LEFT  RIGHT                                 10.       0.7
            -20.                          -1.0
            -10.                          -0.7
             0.0                           0.0
             10.                           0.7
             20.                           1.0
            9999
93NODE-1NODE-2LEFT  RIGHT
```



Linear region B-C-D to be used in steady state solution

1.38 TYPE-94 MODERN-STYLE SiC SURGE ARRESTER COMPONENT

History of Development

(page Repeated)

The EMTP branch component which has type-code 94 is a single-phase true nonlinear element whose dynamics are designed to represent a modern-style silicon-carbide surge arrester with current limiting gap.

The mathematics of the Type-94 model are fully documented in Reference 17. It is strongly recommended that a copy of this paper be procurred from the library by anyone who is considering the use of this component. Details are too involved to be fully covered here.

The computer implementation of the Reference 17 mathematics was performed at the American Electric Power (AEP) Service Corporation in New York City. Dr. Arun Phadke, Chuck Wolf, and perhaps others of that organization remain (as of July 1977) the only persons who have any practical experience with the arrester model. Procurement of the seventeen data parameters is a complication, with the only known measurements to date being applicable to the 765-kV arresters which are used by AEP.

Details related to the acquisition and testing of this AEP surge arrester code are summarized in Reference 8 (Vol. VII, 15-page memorandum dated February 10, 1977). This memo is recommended reading for the uninitiated, too. Highlights include a fully-documented sample simulation, plus five pages of comments by Arun.

EMTP Data Format for Type-94 Arrester Component

Data input for a Type-94 surge arrester component begins with the usual branch card, which is to be punched according to the following format:

ITYPE	Node names		Reference br.		V_{flash}	F_v	F_i	• • •	IOUT
	BUS1	BUS2	BUS3	BUS4					
I2	A6	A6	A6	A6	E6.2	E6.2	E6.2		I1

ITYPE —— Branch type-code "94" is to be punched in columns 1-2 of the card, as a request for the arrester component.

BUS1, BUS2 —— EMTP node names for the two ends of the branch. These are two pieces of 6-character alphanumeric information, to be punched in columns 3-14.

BUS3, BUS4 —— Columns 15-26 are used only for the reference branch feature, for the second or later arrester of a set of arresters which have identical characteristics. If the present arrester is identical to preceding arrester, the user can punch the node names of that preceding arrester (as an ordered pair) in the data fields BUS3 and BUS4. As illustrated by the sample data listing below, parameters V_{flash}, F_v, and F_i are not considered to be part of this check for "identical" characteristics; these three floating-point parameters must always be punched, and can take on any values, irrespective of whether the reference-branch procedure is used.

V_{flash} — Arrester flashover (sparkover) voltage, in units of voltage (whatever they may be, for the problem under consideration).

F_v, F_i — Voltage and current scaling factors (respectively), which allow the same arrester constants to be used without alteration in data cases for which base voltage and current may be different. By definition (see note below):

$$V_{system} = F_v \cdot V_{arrester}$$

$$I_{system} = F_i \cdot I_{arrester}$$

IOUT — A nonzero punch in column 80 requests output of the following arrester variables:

punch "1" for branch current;
punch "2" for branch voltage;
punch "3" for both branch current and branch voltage;
punch "4" for both branch power and energy consumption.

Provided (i.e., if and only if) fields "BUS3" and "BUS4" are blank, six additional cards bearing 18 parameters of the arrester must immediately follow the branch card above. The format and meaning are as follows

E16.0	E16.0	E16.0	E16.0	
K of (2)	b of (2)	b of (1)	Read, but unused at present	Card 1
K_e of (9)	I_c of (9)	E_1 of (10)		Card 2
K_f of (12)	K_0 of (12)	K_1 of (12)		Card 3
K_2 of (12)	W_2 of (16)	K_d of (17)		Card 4
W_0 of (18)	W_1 of (18)	K_e^* of (24)		Card 5
K_3 of (24)	I_3 of (22)			Card 6

The meaning of these parameters is documented in the aforementioned IEEE paper (Ref. 17), portions of which have been reproduced below. It is hoped that the symbol references above are clear. For example, the expression "K of (2)" which is in the first field of the first card means that this data field (columns 1-16) is to be punched with parameter "K" of Eqn. (2) of the IEEE paper. Etc. for the other references.

lation of Dynamic Arrester Performance

The block characteristics of Figure 1 suggest a simple equivalent It would include a nonlinear resistor in series with an inductance hunting diode, the latter to give the common return characteristic.

Since the gap dynamic characteristics were so dominant, the diode was not represented in this study. For the equivalent circuit we may thus write

In this equation, R_b is not a constant. For our purpose we may write

$$R_b i_a = K i_a^{\,b} \qquad (2)$$

Where K and b are constant over a given range of currents, but may vary from one range to another.

During the period immediately following sparkover, $t_o < t < t_1$, the gap voltage increases rapidly as the arc is lengthened. The development of this arc voltage resembles the charging of a capacitor, therefore the relationship chosen to represent this phenomena has form

$$V_g = \int_{t_o}^{t} \frac{(i_a)\,dt}{C} \qquad t_o < t \le t_1 \qquad (8)$$

It was found that the capacitance C for this type of representation is itself a function of arrestor current and time such that

$$\frac{1}{C} = K_c \int_{t_o}^{t} i'_a\,dt \qquad \begin{array}{l} i'_a = i_a, \; i_a < I_c \\ i'_a = I_c, \; i_a \ge I_c \end{array} \qquad (9)$$

where K_c and I_c are constant for a given gap design. Therefore the capacitance is infinite at sparkover and monotonically decreases according to equation (9). If R_r and R_d of Figure 5 are assumed infinite during this first interval of time, then the expression for C given by equation (9) is the same C shown in the equivalent circuit diagram. The final time t_1 for this first interval occurs when the gap voltage reaches a level E_1, which is a constant for a given gap design and a specified arrester rating, thus t_1 is defined by

$$V_g(t_1) = E_1 \qquad (10)$$

During the second stage of gap response, $t_1 < t < t_2$, the arc voltage exhibits a form of negative resistance in that it remains relatively constant at E_1 for high current levels but increases somewhat as the current decreases. This phenomenon is represented by the equation

$$V_g = K_r \int_{t_1}^{t} \frac{K_o - V_g}{K_1 + K_2 i_a}\,dt + V_g(t_1) \qquad t_1 < t \le t_2 \qquad (11)$$

which may be written in the differential form

$$\frac{1}{K_r}\frac{dV_g}{dt} = \frac{K_o - V_g}{K_1 + K_2 i_a} \qquad t_1 < t \le t_2 \qquad (12)$$

where K_r, K_o, K_1, and K_2 are constant for a specified arrester. If R_r in Figure 5 is assumed infinite during this second interval of time, the equivalent circuit may be related to equation (12) by letting

$$E_r = K_o - K_1 i_a - K_2 i_a^{\,2} \qquad (13)$$

$$R_r = K_1 + K_2 i_a \qquad (14)$$

$$C = \frac{1}{K_r} \qquad (15)$$

The final time t_2 for the negative resistance period occurs when a critical level of thermal energy W_2 is reached so that t_2 is defined by

$$\int_{t_1}^{t_2} V_g i_a\,dt = W_2 \qquad (16)$$

During the thermal decay period, $t_2 < t < t_3$, the gap voltage tends to decrease as the arc heats the arc chamber walls. This effect is represented by adding a negative energy-dependent term to the integrand in equation (11), that is

$$V_g = K_r \int_{t_2}^{t} \left[\frac{K_o - V_g}{K_1 + K_2 i_a} + \frac{W}{K_r}(K_d - V_g)\right] dt + V_g(t_2) \qquad t_2 < t \le t_3 \qquad (17)$$

where K_d is a constant and the thermal energy factor is given by

$$W = W_o + W_1 \int_{t_1}^{t} V_g i_a\,dt \qquad (18)$$

where W_o and W_1 are constant. Equation (17) may also be written in the differential form

$$\frac{1}{K_r}\frac{dV_g}{dt} = \frac{K_o - V_g}{K_1 + K_2 i_a} + \frac{W}{K_r}(K_d - V_g) \qquad t_2 < t \le t_3 \qquad (19)$$

The equivalent circuit for the gap given in Figure 5 is therefore defined over this interval by equations (13) - (15) and the relationships

$$E_d = K_d \qquad (20)$$

$$R_d = \frac{K_r}{W} \qquad (21)$$

The final time t_3 for the thermal decay period occurs when the arrester current deceases to a very low level, a region of arc instability. Therefore, t_3 is defined by

$$i_a(t_3) = I_3 \qquad (22)$$

$$\frac{di_a}{dt}(t_3) < 0 \qquad (23)$$

The region occurs immediately prior to the arrester interruption time t_4. During this interval, $t_3 < t < t_4$, the gap voltage rises rapidly. This phenomenon causes the current to decrease at a much greater rate which speeds up the desired interruption. The arc instability may be simulated by modification of equation (11), that is instability

$$V_g = K_r \int_{t_3}^{t} \frac{K'_o - V_g}{K_1 + K_3 i_a^{\,2}}\,dt + V_g(t_3) \qquad t_3 < t \le t_4 \qquad (24)$$

In order to decipher these equations, go get a complete copy of this IEEE paper (Ref. 17)

As an illustration of Type-94 EMTP surge arrester data, consider the following usage. This is taken from UTPF Test Case #57 ; the solution of which is fully documentel in the EMTP memo of February 10, 1977.

```
94    N11                     8.5     1.0   1.0
                5.0            .27                  .0001                        4
               1.4E8           .268                  5.0
              10000.           7.0                   2.0
                 .02           .0006                 4.5
                200.           4.0E6                 10.
               4000.           .05
-1     B1.    B3
-1     B3     B2     B1     B3         .658    27.4     5.    0
       B2     AB2                                                                1
94    AB2                          1.E-8                                         1
                    N11     25.5   3.0     2.0                                   1
      N0     N1          -1.                                                     4
      B0     B1          -1.               1000.
                                           1000.
14     30     30.        60.
                                                      -1.
```

Two identical surge arresters (except for flashover voltage and scaling factors) are being defined here. The first, which is connected between node " N11" and ground has flashover voltage equal to 8.5 (in whatever units are being used; kV ?) and scaling factors of unity; there is no reference-branch usage (all parameters of the arrester are supplied with it). The second arrester connects node " B2" to ground, and is a copy of the first (the reference-branch procedure is used). Flashover voltage for this 2nd arrester is 25.5 , and voltage and current scaling factors are 3.0 and 2.0 , respectively, note.

The following explanation of voltage and current scaling factors F_v and F_i was taken from the EMTP memorandum dated February 10, 1977:

> Since the constants are usually derived from a prorated arrester module, they correspond to a physical description of the module. Typically, one would calculate the constants to describe the kiloamperes - kilovolts relationship for the arrester module. The usual EMTP representation of a power system is in some per unit system. Rarely would the power system be modeled on the physical voltage - current scales of a prorated arrester module. It is therefore necessary to effect a scale change before the arrester model can be directly used in the EMTP.
>
> The necessary scale changes are implemented through the voltage and current scale factors F_v and F_i entered on each Type 94 card:
>
> $$V_{system} = F_v \cdot V_{arrester}$$
>
> $$I_{system} = F_i \cdot I_{arrester}$$
>
> Consider the two simulations in the test case as examples of the use of F_v, F_i. In both simulations, the arrester module used is the same, so that the constants of the arrester model also are the same. The current base for the first system (buses $N_1 - N_{11}$) is 1 KA. V_{flash} for the arrester moduel is 8.5 KV. Since it is desired to simulate the discharging of a line energized to 10 KV through this arrester module, F_v and F_i are both set equal to 1.0 and a generator voltage of 10 is used.

Now consider the second system operating at 30 KV (Generator voltage = 30) with a base current of 2 KA. A line similar (though not identical) to the one of the previous simulation is connected between buses B1 and B2. Flashover voltage for the arrester is set at 25.5. The flashover voltage of a single module is 8.5 KV, so that the voltage and current conversion factors must be set at $F_v=3.0$ and $F_i=2.0$. Note that this selection closely parallels the actual test of this nature, which would require a series connection of three arrester modules each with a flashover voltage of 8.5 KV. The voltage and current waveforms from EMTP output are expressed in system variables, consequently although all the voltages and currents for the two cases are approximately similar to each other, the voltage and current scales for the two cases differ by a factor of 3 and 2 respectively.

The familiar EMTP requirement of isolating true nonlinear elements by distributed-parameter lines also applies to the Type-94 AEP surge-arrester component. Refer to Section 1.3-A-a of the present EMTP User's Manual. Later extension to a 3-phase component seems inevitable, if there is sufficient interest on the part of users (see Section III-E of the EMTP memo dated May 15, 1976 ---- Vol. V of Ref. 8).

Storage requirements for the Type-94 surge arrester component are easily calculated. First, each arrester contributes one entry to EMTP List number 9 (the nonlinear element table). The contribution from each arrester to List number 10 (points defining nonlinear characteristics) depends upon whether the reference branch procedure is used; 11 cells are required if it is, while 18 cells are required if it is not.

The reader is advised not to confuse silicon-carbide (SIC) arresters ---- for which the present Type-94 nonlinear element was designed ---- with the newer zinc-oxide arresters. As of July 1977, the latter are still believed to be somewhat experimental, and are the subject of ongoing development. Zinc-oxide arresters are radically different in that they have no flashover gap; the nonlinear element is extremely nonlinear, and is simply permanently connected to the system (drawing a leakage current in the steady-state). At present, the only EMTP modeling which has been designed especially for zinc-oxide arresters is the Type-17 EMTP source component (see Section 1.6).

The Type-94 surge arrester component is of course an open circuit during the steady-state phasor solution for initial conditions. Then, should a flashover occur at some particular time during the simulation, a message is printed. The following is an example, taken from UTPF Test Case #57:

```
ARRESTER "  A82"  TO "      "  FLASHOVER AT TIME   .32750E-02  SEC.
```

Finally, when the arrester seals again (becomes an open circuit once again), a second message is printed, such as:

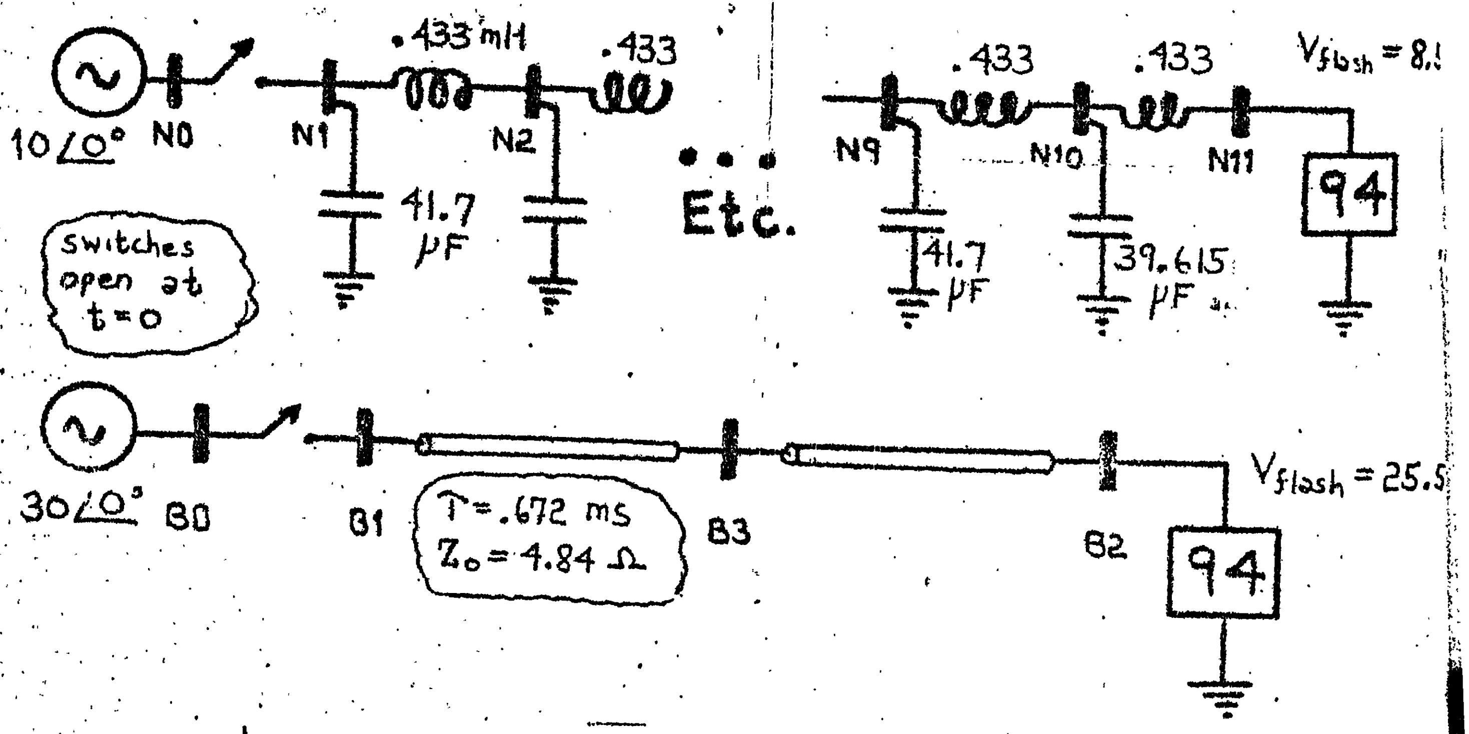
```
ARRESTER "  A82"  TO "      "   CLEARED  AT TIME   .27050E-02  SEC.
         PER UNIT ENERGY DISSIPATED =   .983621E-02
```

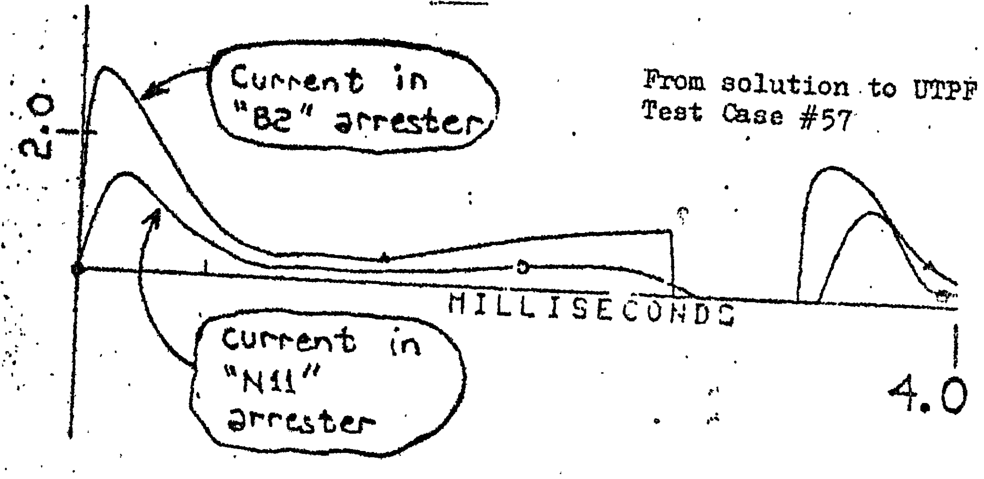
Note that the dissipated energy is also printed. This is in per unit, and is just the energy which has been absorbed since the last firing. This figure is totally independent of that which comes from a "4"-punch in column number 80 of the branch card for the arrester ---- for which physical units are used, and with the energy accumulation beginning at time zero.

The term "per unit" which is used for arrester energy printout is based on the user-supplied scaling factors F_v for voltage and F_i for current (columns 33-44 of first data card for arrester). One can convert between absolute energy and per unit energy using the following definition:

$$P\,[\text{absolute}] \;=\; F_v \cdot F_i \cdot P\,[\text{per unit}]$$

If the user specifies source amplitudes to be in volts and amps, then the unit of absolute energy is the Joule ; but if kV were used for the units of source voltage (as in UTPF Test Case #57 illustrated in this section), then the unit of absolute power is the megaJoule .





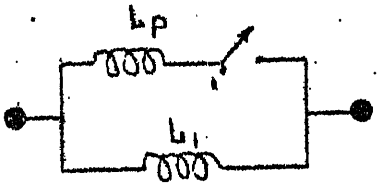
From solution to UTPF Test Case #57

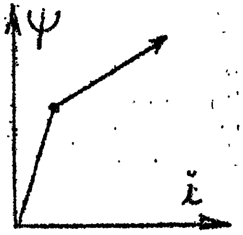
1.4 SWITCH CARDS

Cards inputted as part of this class of data input include the following:

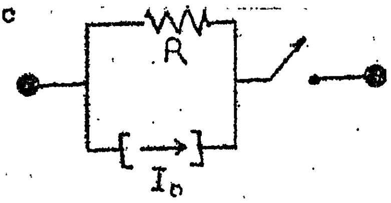
1. "Ordinary" switches, for which the voltage drop is zero when closed, and for which the current is zero when open. Such switches bear the type code ITYPE = 0 (columns 1-2 of data card), or possibly ITYPE = 76 for exceptional "STATISTICS" switches.

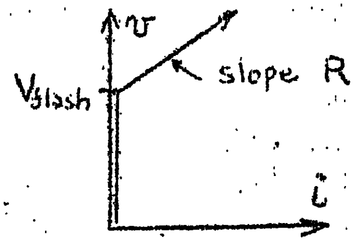
2. Switched-inductance element, wherein a two-section piecewise-linear saturation curve of flux vs. current can be represented. Switched-inductance elements bear type code ITYPE = 93 (columns 1-2 of data card). See Section 1.41 .



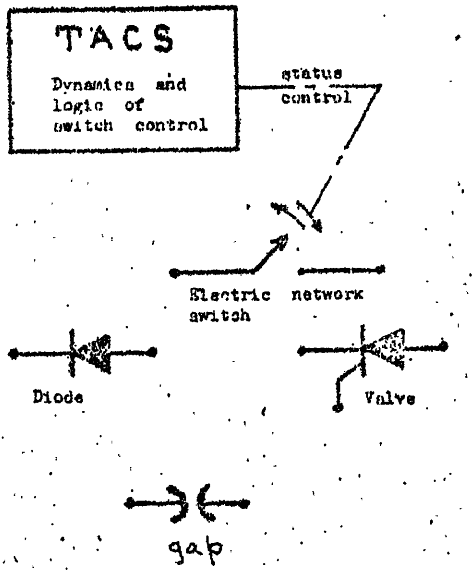


3. Switched-resistance element, wherein the v-i characteristic shown can be represented. The switched-resistance element bears type code ITYPE = 92 (columns 1-2 of data card). See Section 1.42 .





4. TACS-controlled switch, wherein the switch status is controlled by TACS. Recall that TACS is the EMTP "digitally-simulated analog computer," as fully described in Section 8. . The TACS-controlled switch bears type code ITYPE = 11, 12 or 13 (cols 1-2 of data card). Important special cases of this general component capability are diodes and valves (as used for ac/dc conversion). See Sections 1.43, 1.44 and 1.45 for details.



Such datacards are collectively referred to as switch cards, since in all cases the computer model of the element in question involves a "perfect" or "ordinary" switch. Such cards follow the regular branch cards, and precede the source cards. Other points worth noting are as follows:

1. If a case has no switches, then only the blank termination card alone represents this data input type.
2. If a case starts from zero initial conditions, then no switches are necessary for connecting voltage and current sources to the network at zero time, provided the sources remain connected throughout the study.

1.40 ORDINARY SWITCHES

Switches which do not involve linear elements are of five different basic types or classes, as follows:

Class 1 : Conventional (i.e., deterministic) time-controlled switch.

Class 2 : Voltage-controlled (flashover) switch.

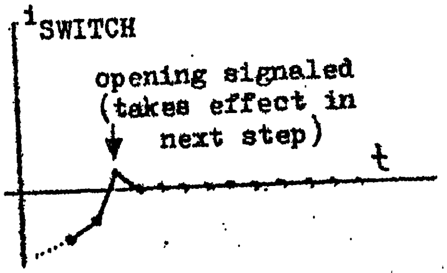
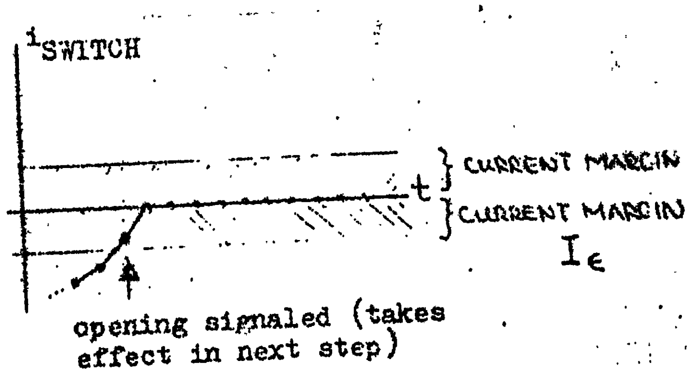
Class 3a: "STATISTICS" switch (a time-controlled switch where the closing time is a random variable.

Class 3b: "SYSTEMATIC" switch (a time-controlled switch where the closing time is systematically (regularly) varied).

Class 4 : "MEASURING" switch, which is permanently closed for all time, by definition. It is used just for current or power and energy monitoring.

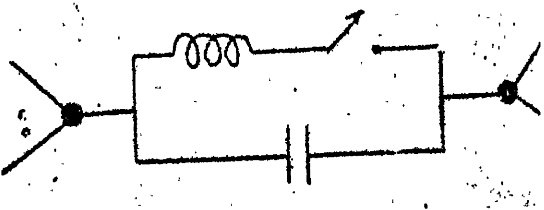
Class 5 : TACS-controlled switch (including diodes, valves, etc.).

Class 1 :
Time-controlled switch (circuit breaker pole): Switch is open originally, closes at $t \geq T_{CLOSE}$ and tries to open again after $t \geq T_{OPEN}$. In option A the opening is successful as soon as the current i_{SWITCH} has gone through zero (detected by a sign change in i_{SWITCH}). In option B the opening is successful as soon as $|i_{SWITCH}| <$ CURRENT MARGIN or as soon as i_{SWITCH} has gone through zero. After a successful opening, the switch will stay open.

Option A	Option B
Opening when i_{SWITCH} goes through zero (set CURRENT MARGIN = 0)	Opening when $|i_{SWITCH}| <$ CURRENT MARGIN or i_{SWITCH} goes through zero (set CURRENT MARGIN > 0)
	

Class 2 :
Flashover-controlled switch (gap): Switch is open originally and tries to close after $t \geq T_{CLOSE}$. The closing is successful as soon as the absolute value of the voltage across the switch is $\geq$ FLASHOVER VOLTAGE. After switch has closed, it waits until the time delay T_{DELAY} has elapsed and then tries to open again with the same current criteria as in option A and B above. The sequence "(1) flashover-controlled closing $\Rightarrow$ (2) elapse of time $T_{DELAY} \Rightarrow$ (3) current-controlled opening $\Rightarrow$ back to (1)" remains effective throughout the study (see figure below).

There are cases where the voltage across the gap oscillates around the true value. An example of this is the case of an inductance "hanging in the air", as per the sketch. To avoid such problems, the gap voltage for checking flashover is computed as the average of the last two time-step figures:



$$v_{gap}(t) = \left(\frac{v(t) + v(t-\Delta t)}{2} \right)$$

	Class 1 (time-controlled switch)	Class 2 (flashover switch)	Class 4 ("MEASURING" switch)
Columns 15-24 (in seconds)	Actual switch closing time. T_{close}	Time before which the switch is prevented from flashing over. T_{close}	—
Columns 25-34 (in seconds)	Time before which opening will not be allowed. T_{open}	Time elapse after flashover, before which opening will not be allowed. T_{delay}	—
Columns 35-44 (in units of current)	Current margin which is used to determine when switch opening is possible. I_{ϵ}		—
Columns 45-54 (in units of voltage)	—	Voltage which must be exceeded for switch to close. V_{flash}	—
Columns 55-64	—	In rare cases, to be used with care; "PART ENTER"	"MEASURING "

	Class 3a "STATISTICS" switch			Class 3b "SYSTEMATIC" switch		
	independent	dependent		independent	dependent	
Columns 15-24 (in seconds)	Mean closing time. $\overline{T}$	Mean $\overline{T}_R$ of random time delay T^R_{random}		Mid-time T_{mid} if START = 0. Beginning time T_{beg} if START [illegible]	constant delay time. T^D_{offset}	
Columns 25-34 (in seconds)	Standard deviation of switch closing time, σ	[illegible] σ_R of random time delay T^R_{random}		(Size of time increment per step). ΔT	—	
Columns 35-44	—	—		Number of [illegible]	—	
Columns 45-54	—	—		—	—	
Columns 55-64 (A10 format)	"STATISTICS"	"STATISTICS"		"SYSTEMATIC"	[illegible]	
Columns 65-70 (A6 format)	possibly "TARGET"	BUS5	Node names of reference switch	possibly "TARGET"	BUS5	Node names of reference switch
Columns 71-76 (A6 format)	—	BUS6		—	BUS6	

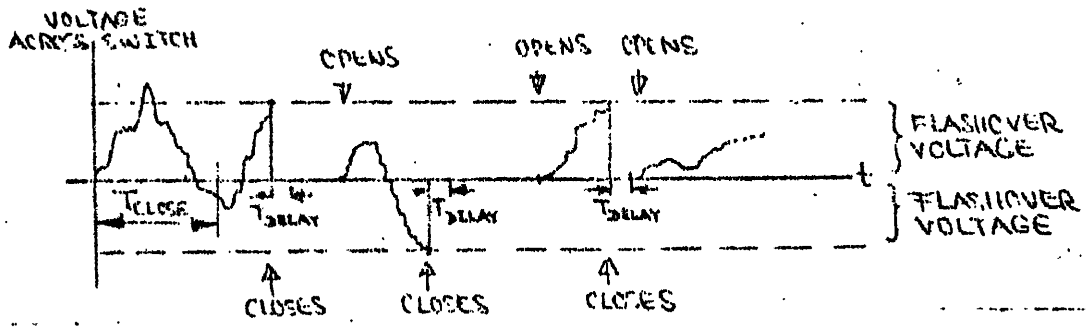
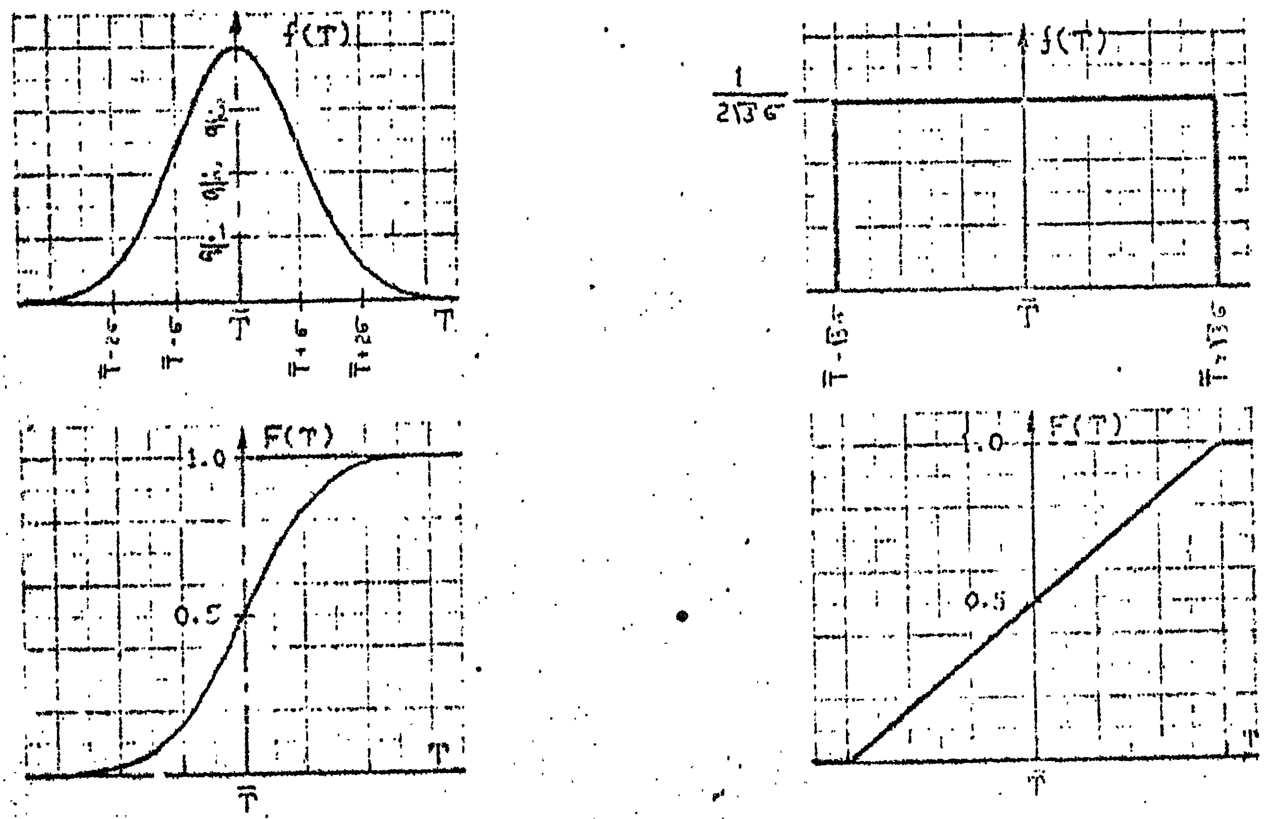


Fig. 1. Sample illustrative operation of flashover-controlled switch.

Class 3a:
"STATISTICS" switch

A statistical overvoltage study consists of "NENERG" (miscellaneous data parameter; see Section 1.0h) separate internally-generated simulations, the peak voltages of which are then processed statistically. The data case in question for such a study contains one or more switches the closing times of which are random variables. Such randomly-closed switches are called "STATISTICS" switches, so named after the key request word "STATISTICS" which must be punched in columns 55-64 of the switch card in question. "STATISTICS" switches are always initially open (in particular, they are always treated as being open for the phasor steady-state solution); they then close once at the appropriate random times (as determined by their probabilistic specifications), never to open again.



a) Gaussian (normal) distribution. IDIST = 0 (and ITYPE ≠ 76).

b) Uniform distribution. IDIST = 1 (or ITYPE = 76).

Fig. 2. Available probability distributions for the closing time T_{close} of a "STATISTICS" switch. Density functions f(T) are shown above, and cumulative distribution functions F(T) below.

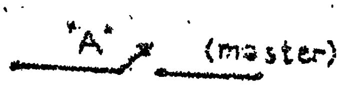
The closing time T_{close} for each "STATISTICS" switch is randomly varied according to either a Gaussian (normal) distribution or a uniform distribution, as illustrated in Fig. 2. Choice as to distribution type is generally controlled by appropriate selection of variable "IDIST" (statistics miscellaneous data parameter; see Section 1.1a) by the user. Then with all switch type codes "ITYPE" (cols. 1-2 of the switch card) zero or blank, all "STATISTICS" switches will use Gaussian distributions if "IDIST" is zero, or uniform distributions if "IDIST" is unity. In order to use both distribution types within the same data case, the user makes "IDIST" equal to zero, and leaves the Gaussian-distributed switches with type code "ITYPE" equal to zero or blank; the exceptional switches which are to have uniform distributions are then flagged by punching the type code "ITYPE" equal to 76 . Fig. 2 illustrates the two available distribution types for "STATISTICS" switches. The mean closing time $\overline{T}$ and associated standard deviation σ are specified by the user on the one or more "STATISTICS" switch cards.

In addition to switch closing-time variation caused by each switch's own distribution, there is an added random delay which is the same for all switches, provided the user has given variable "ITEST" (statistics miscellaneous data parameter; see Section 1.1a) a value of zero or blank. This added random delay which is applied equally to all "STATISTICS" switches is referred to by the term "reference angle"; it follows a uniform distribution always, the probability distribution for which is specified using parameters "DEGMIN" , "DEGMAX" , and "STATFR" of the statistics miscellaneous data card (see Section 1.1a). Line printer output for a statistical overvoltage study will show the reference angle for each energization, in approximately the columns which are normally used for the step number and time value (marked "STEP" and "TIME") of a conventional deterministic (non-"STATISTICS") data case. The numerical value printed out will be in degrees, and will lie somewhere between "DEGMIN" and "DEGMAX" , of course. If the user punches "ITEST" equal to unity, the reference angle will simply be constrained to always be zero —— which is mathematically equivalent to not having any added random delay.

The preceding discussion about "STATISTICS" switches mentioned nothing about the possible dependence of the closing time of one switch on that of a second switch (with both switches being "STATISTICS" switches). Where no such dependence exists, switch cards are completely independent, and the parameters affecting any one switch are [illegible] on the switch card for that switch. This is perhaps the most common, but certainly the simplest, usage.

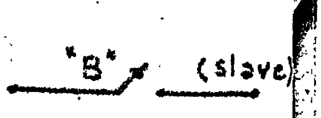
But there also is the capability for dependent "STATISTICS" switches. The closing time of a switch labeled "B" can be made equal to the sum of two components:

$$T^B_{close} = T^A_{close} + T^B_{random}$$



where:

T^A_{close} = previously-determined closing time of another "STATISTICS" switch, labeled here as switch "A" . This is a random variable, note, not a constant.



T^{B}_{random} = random time delay having mean $\overline{T}_B$ and standard deviation σ_B (parameters as punched on the data card for switch "B"). If desired, the mean $\overline{T}_B$ of this component can be negative. The only constraint which must be kept in mind is that the resulting actual switch closing times must only very infrequently turn out to be less than the beginning time of the simulation (which is usually zero).

But switch "A" might itself in turn depend on a third switch "Z" . The EMTP allows an arbitrary number of such dependencies. In terms of the above example, switch "B" is called a dependent (or slave) switch, while switch "A" is the reference (or master) switch. An arbitrary number of levels of servitude are permitted.

The identification or specification of reference switch "A" in the above example is actually made using the two 6-character alphanumeric bus names of the switch. The names of this reference switch "A" are to be punched using 2A6 format in columns 65-76 of the data card for dependent switch "B" . This is the way in which the EMTP distinguishes between dependent and independent "STATISTICS" switches : whether or not columns 65-76 are non-blank.

A specialized data-convenience option is provided by the "TARGET" feature. Any non-dependent "STATISTICS" switch can be designated as a "TARGET" switch by punching this key word in columns 65-70 of the switch card. Only one such designation is permitted in any one data case. The effect is that all other non-dependent "STATISTICS" switches will be internally given mean closing times which are equal to the mean closing time of the "TARGET" switch. Several details might be noted:

a) Only convenience of data punching is involved, for the "TARGET" option does not extend the modeling capability at all.

b) Nothing has been said about standard deviations σ . It is only the mean closing time $\overline{T}$ which is affected by the use of "TARGET" .

c) Columns 15-24 of non-"TARGET" , non-dependent "STATISTICS" switch cards can be left blank (since the mean closing time will come from the "TARGET" switch).

Random switch opening

All of the preceding text of this section applies to the random closing of "STATISTICS" switches. Then along came the demand for random opening late in 1979 (see Ref. 8, Vol. IX, 6 November 1979, pages EOVN-1 to 3). Two key paragraphs from the memo writeup are reproduced here:

Special Switch-Card Flag for Random Opening

For random opening of a switch, columns 45-54 of the switch card are to be punched with the special numerical flag "3333." . Otherwise, data fields ar unchanged (see pages 27a and 27e of the EMTP User's Manual) ---- except that "closing" is to be read as "opening" wherever it is encountered. That is, the mean opening time $\overline{T}$ goes in columns 15-24, the standard deviation σ goes in columns 25-34, and the key-word "STATISTICS" must be punched in columns 55-64. The use of "TARGET" or dependency of switches is also allowed, according to the same rules as before. In fact, the user can mix random opening and random closing within the dependency chain, if so desired.

First, a word of caution about opening times. A switch which is to randomly open starts out as being closed in the steady-state, and it is subsequently inhibi from opening until the time which is determined by rolling the dice. But switch cu is not generally zero at this instant of time. The actual opening is delayed until switch current goes through zero. If this never happens, the switch will never ope

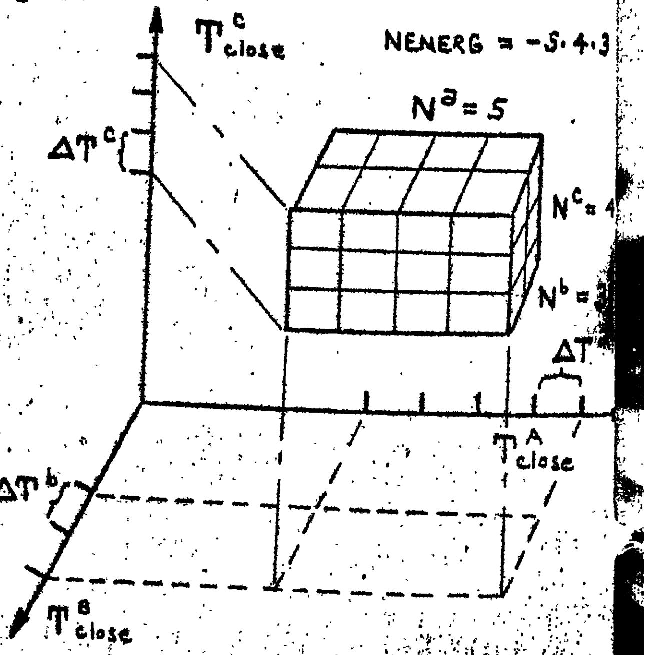
The user of random opening should read Section 1.0e12 , wherein TENERG can be defined using "TIME OF DICE ROLL" . It is crucial as of April 1980 that TENERG be negative in the case of random opening, as explained on page EOVN-3 of the memo. Either this is done automatically by "SYSDEP" (most computer versions should be set up that way), or else it must be done manually using the request of Section 1.0e12 .

Class 3b :

"SYSTEMATIC" switch

An EMTP study which involves a "SYSTEMATIC" switch consists of |NENERG| (miscellaneous data parameter; see Section 1.0h) separate internally-generated simulations, the peak voltages of which are then processed and tabulated statistically. Each "SYSTEMATIC" switch has its closing time systematically (regularly) varied between a given beginning and ending time, in steps which are uniformly spaced. Such systematically-varied switches are named "SYSTEMATIC" switches after the key request word "SYSTEMATIC" which must be punched in columns 55-64 of the switch card in question. "SYSTEMATIC" switches are always initially open (in particular, they are always treated as being open for the phasor steady-state solution); they then close once at the appropriate systematic time, never to open again.

Note specifically the minus sign which is a part of "NENERG" ; it is used to definitively distinguish a "SYSTEMATIC" data case from a "STATISTICS" data case, as the data input begins.



The user is warned of the potentially enormous number of energizations which can be involved in a "SYSTEMATIC" data case. As an example, consider a data case which has three independent "SYSTEMATIC" switches. Then one can think of the internally-generated energizations as being a methodical exploration of a rectangular region of the 3-dimensional vector space of switch closing times (see sketch above). For example, if switch "A" were to take 6 steps, switch "B" 5 steps, and switch "C" 4 steps, then a total of |NENERG| = 120 = 6 x 5 x 4 energizations would be internally generated by the EMTP.

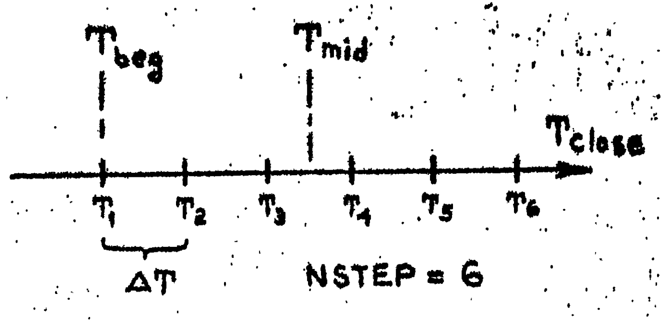
Dependency among "SYSTEMATIC" switches is permitted, and deserves an explanation. The general concept is similar to that for "STATISTICS" switches, but with several crucial differences. Let switch "B" be the dependent switch, and switch "A" the reference switch, as before. Then the closing time of dependent switch "B" is not independently varied, but rather is offset by a fixed amount from the closing time of the reference switch "A" :

$$T^B_{close} = T^A_{close} + T^B_{offset}$$

Here T^B_{offset} is a constant (it has the same value for all energizations). Rather than a beginning (or mid) time, a step-size, and a number of steps, the input time-data for a dependent "SYSTEMATIC" switch consists of only the constant offset time, which is to be punched in columns 15-24. A dependent "SYSTEMATIC" switch does not increase the dimensionality of the vector space of switch closing times which is to be systematically explored, note. The mechanism for indicating the dependence of a "SYSTEMATIC" switch is identical to that which is used for a "STATISTICS" switch; the node names of the reference switch are to be punched in columns 65-76 of the card for the dependent switch.

For each non-dependent "SYSTEMATIC" switch card, the size of the time increments ΔT is to be punched in columns 25-34 . The number of steps NSTEP is to be punched in columns 35-44 . The third and final time-parameter is to be punched in columns 15-24 , and it depends on the value of "ITEST" (miscellaneous data parameter of Section 1.1a) :

$$ITEST = \begin{cases} 0 \Rightarrow \text{punch the mid-time } T_{mid} \\ 1 \Rightarrow \text{punch the beginning time } T_{beg} \end{cases}$$



A specialized data-convenience option is provided by the "TARGET" feature. Any non-dependent "SYSTEMATIC" switch can be designated as a "TARGET" switch by punching this key word in columns 65-70 of the switch card. Only one such designation is permitted in any one data case. The effect is that all other non-dependent "SYSTEMATIC" switches will be internally given mid-times or beginning times which are equal to that of the "TARGET" switch. Several details might be noted:

a) Only convenience of data punching is involved, for the "TARGET" option does not extend the modeling capability at all.

b) Nothing has been said about the time increment ΔT and the number of steps NSTEP . It is only the mid-time or the beginning time which is affected by the use of "TARGET" .

c) Columns 15-24 of non-"TARGET" , non-dependent "SYSTEMATIC" switch cards can be left blank (since the beginning or mid-tim will come from the "TARGET" switch).

Class 4 :

"MEASURING" switch

By definition, a "MEASURING" switch is permanently closed for all time (including any phasor steady-state solution for initial conditions). It is used for the monitoring of current, or power and energy, in places where these quantities are not otherwise available. This may be for EMTP output purposes (printing or plotting), or in conjunction with use of the Type-91 TACS signal source (see Section 8.5.4).

To request a measuring switch, the key word "MEASURING" is to be punched in columns 55-64 of the switch card. The terminal bus names "BUS1" and "BUS2" must be punched as 2A6 information in columns 3-14, of course. Then it is only a possible column-80 punch for output purposes which is needed; the rest of the data card can be left blank.

a) Rules for Ordinary Switches

0) The switch type code (data card field ITYPE ; columns 1-2) is zero. Either the zero may be punched, or the field may be left blank.

   A special exception is type code ITYPE = 76 . This is for a "STATISTICS" switch that the user wants to follow a uniform distribution, in a problem with one or more "STATISTICS" switches which follow Gaussian distributions (statistics misc. data parameter "IDIST" equal to zero).

1) Specify the two terminal nodes by names (fields BUS1 and BUS2 ; columns 3-14). One of the nodes may be ground, indicated by a blank field for the associated name.

2) A node which is not a voltage source may have only one switch connected to it (a voltage source or ground may have any number of switches connected to it).

Comment: This one-switch restriction is not imposed by mathematical reasoning, but rather has been assumed so as to simplify the computer programming. To satisfy this restriction, the user can insert small resistances or inductances to separate switches. Very small resistances can cause numerical problems in the form of ill-conditioned matrices. It is believed to be generally preferable to use small inductances, since the equivalent resistance $2L/\Delta t$ (see Ref. [illegible]) is not as small for small Δt . A reasonable number might be 10 μH, which corresponds to about 10 m [illegible]

3) No switch is permitted between two voltage sources, or between one voltage source and ground. Such a condition is absurd, of course, leading to a contradiction. The program will flag such a situation with an error message.

4) If a switch connects a voltage source to a current source, then the current source is ignored whenever the switch is closed.

5) Floating-point parameters and special request word which are to be punched on an "ordinary" switch card are dependent upon switch Class, as per the previously-displayed tables.

6.) If transients start from a non-zero ac steady-state condition, make $T_{CLOSE} < 0$ for time-controlled switches which are closed in the ac steady-state condition. Flashover-controlled switches will always be open in the ac steady-state; if the user punches $T_{CLOSE} < 0$ on these switch types, the program will change it to $T_{CLOSE} = 0$ with the message "T_{CLOSE} CHANGED TO 0."

For a "STATISTICS" switch, it is the mean closing time $\overline{T}$, the expected value or mathematical expectation of the random closing time T_{close}, $\overline{T} = E\{T_{close}\}$, which is inputted by the user. Not only had this mean better be positive, but the particular switch closing times generated from the specified distribution had better almost always be positive also. This is because negative time in an EMTP simulation corresponds to the sinusoidal steady-state solution, into which we are powerless to inject switching events. To avoid such trouble, the simple requirement that $\overline{T} - A \cdot \sigma$ be positive is made upon data input, where "A" is a constant which depends upon distribution type:

$$A = \begin{cases} \text{SIGMAX} & \text{if Gaussian (normal) distribution. See Section 1.1 definition (user-supplied parameter which is defaulted to 4.0 if left blank).} \\ \sqrt{3} & \text{if uniform distribution} \end{cases}$$

A fatal EMTP error termination is the result, if this check is not satisfied for all "STATISTICS" switches. For a Gaussian distribution, this check ensures that any particular switch closing time turning out negative has probability which is less than 0.005% ; for a uniform distribution, this guarantees that all switch closing times will always be positive (see Fig. 2). For dependent switches in which Gaussian and uniform distribution offsets are mixed, the "SIGMAX" value is applicable to the Gaussian components and the square root of three is used on all uniform components.

7) For either a "STATISTICS" or a "SYSTEMATIC" switch, the special request word "STATISTICS" or "SYSTEMATIC" must be punched in the field of columns 55-64. Be sure to spell such request words correctly, and begin in column number 55 ; if not, a Class-1 switch will result, rather than the desired Class-3a or Class-3b switch.

8) If a switch is chosen to be the "TARGET" switch of either a "STATISTICS" or a "SYSTEMATIC" data case, then this key word "TARGET" must be punched in columns 65-70 of that switch card. Only one switch card of a given data case might be so punched (there is at most one "TARGET" switch, by definition).

9) A dependent "STATISTICS" or "SYSTEMATIC" switch is to have the terminal node names of the reference switch punched in columns 65-76 . The format is 2A6 .

10) Output options for printing and/or plotting are punched in column 80, as follows:

"1" punch is a request for switch current output;
"2" punch is a request for switch voltage output;
"3" punch is a request for both switch current and voltage output;
"4" punch is a request for switch power and energy flow (see Section 1.8 for details).

Warning : If a case starts from nonzero sinusoidal steady-state initial conditions with a switch current nonzero, this switch current value will be printed and plotted incorrectly as zero at time zero. However, the subsequent simulation itself is always correct, being unaffected by this isolated output difficulty. In such a case, the extraneous zero output value for switch current at time zero should simply be ignored by the user.

The column positions and mode in which the various switch parameters for an "ordinary" switch are to be punched are indicated by the following format:

ITYPE	Node names		Time Criteria			I_ϵ or	Flashover Voltage	Special Request Word Column	reference switch names, or "TARGET"		Etc.	Output option
	BUS1	BUS2	T_{close} or $\bar{T}$	T_{open} or T_{delay}	σ ΔT	NSTEP	V_{flash}		BUS5	BUS6		
I2	A6	A6	E10.0	E10.0		E10.0	E10.0	A10	A6	A6		I1

Sample of "ordinary" switch specification

As an example of the preceding "ordinary" switch rules and data format specification, consider the four sample usages of the following listing:

1	BUS-1	BUS-2		.001					
2	BUS-3	BUS-4	.0005	.002	.001				
3	GAP-1	GAP-2			.1	1.E6			
4	JDAYGA	JDAYA	.002	.0004			STATISTICS		
5	AS	ASW	.003	.0001	12.		SYSTEMATIC		
6	BS	BSW	.004	.0005			STATISTICS	TARGET	
7	CS	CSW	.002	.0001	8.		SYSTEMATIC	TARGET	
8	DS	DSW	.006	.0002			STATISTICS	AS	ASW
9	ES	ESW	-.005				SYSTEMATIC	CS	CSW

As verbal explanation of these:

1. breaker pole "BUS-1" to "BUS-2" closes at t = 0 and opens after t ≥ 0.001s as soon as current goes through 0.

2. breaker pole "BUS-3" to "BUS-4" closes at t ≥ 0.0005s and opens after t ≥ 0.002s as soon as absolute value of switch current is <0.001 AMPS or goes through zero.

3. gap "GAP-1" to "GAP-2" closes whenever voltage across switch becomes ≥ 1 000 000 VOLTS and opens as soon as absolute value of switch current becomes <0.1 AMPS or goes through zero.

4. "STATISTICS" switch connecting node "JDAYGA" with node "JDAYA " has mean closing time of 2.0 msec and associated standard deviation of 0.4 msec . Assuming that statistics miscellaneous data parameter "IDIST" is zero, the probabilistic distribution will be Gaussian (normal). This assumes that there is no "TARGET" "STATISTICS" switch in the data case.

5. Non-dependent "SYSTELATIC" switch that connects node "AS " with node "ASW " . The mid-closing-time is 3.0 msec , assuming "ITEST" is zero and that the data case in question has no "TARGET" [illegible] the switch is to be varied in steps of size 0.1 msec ; [illegible] be taken.

6. "STATISTICS" switch connecting node "BS " with node "BSW " is the "TARGET" switch for the data case in question. All non-dependent "STATISTICS" switches of the data case will have the same mean closing time of 4.0 msec . That is, the information which is punched in columns 15-24 of all other non-dependent "STATISTICS" switches is over-ridden by the value for the present "TARGET" switch. The standard deviation of the closing time for this "TARGET" switch is 0.5 msec .

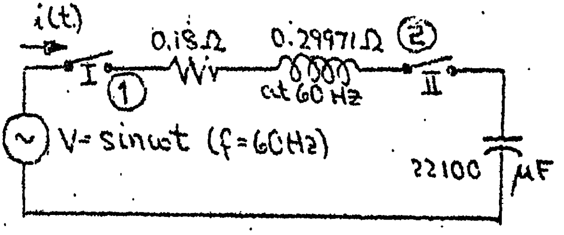
7. "SYSTEMATIC" switch connecting node "CS " with node "CSW " is the "TARGET" switch for the data case. All non-dependent "SYSTEMATIC" switches of the data case have the same mid-closing time of 2.0 msec (if "ITEST" is zero), or the same beginning closing time of 2.0 msec (if "ITEST" is unity). The information of columns 15-24 on all other non-dependent "SYSTEMATIC" switch cards is over-ridden by the value on the "TARGET" switch card (that now being discussed). The closing time of this switch is to be varied through 8 steps; the step-size is 0.1 msec .

8. The switch connecting node "DS " with node "DSW " is a dependent "STATISTICS" switch. Its reference switch is the one connecting node "AS " with node "ASW " . Note that (or remember that) the reference switch must have been previously inputted. The closing time of the present switch is delayed from that of its reference by a random delay time which has a mean of 6.0 msec and a standard deviation of 0.2 msec .

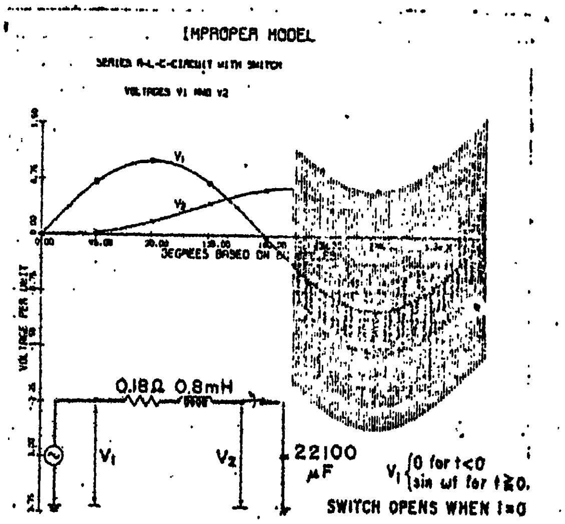
9. The switch connecting node "ES " with node "ESW " is a dependent "SYSTEMATIC" switch. Its reference switch is the one which connects node "CS " with node "CSW " . The closing time of the present switch is offset (delayed) from that of its reference by a constant offset time of -5.0 msec . That is, the present switch will always close 5.0 msec before closure of the reference switch.

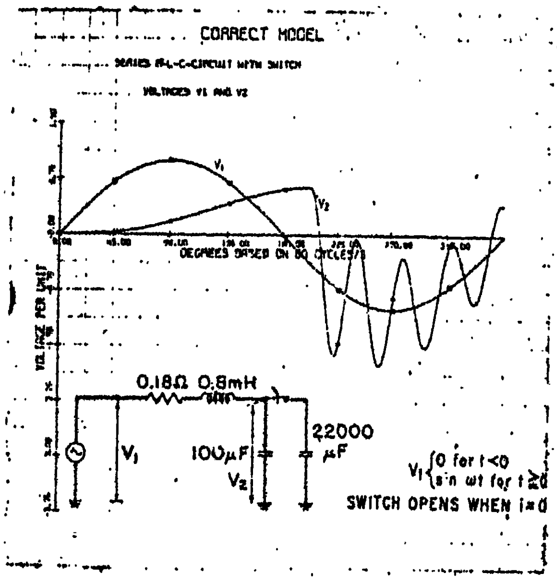
to follow

c) REMARKS ON OPENING ACTION

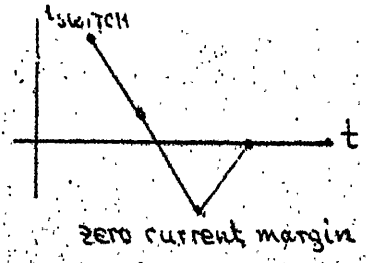


The circuit on the left is used to indicate the difficulties which can result during the opening of a switch in a physically improper model: Assume that both switches I and II are closed at $t = 0$. Then a transient current $i(t)$ will charge the capacitor. Switch II shall open as soon as $i(t)$ is approximately zero. In the time step in which the opening is signaled (i_{switch} changing sign in option A, $|i_{switch}| <$ CURRENT MARGIN or i_{SWITCH} changing sign in option B), there will still be a residual current Δi through the inductance L. The next time step will find switch II open with no path left to dissipate the rest energy $\frac{1}{2} L(\Delta i)^2$. As a result, the computer cannot find the correct voltage $V_2(t)$ anymore (see left figure below). It should be noted that the incapability of the computer is a consequence of improper modeling. By putting a very small fraction of the capacitance over onto the left side of the switch, a path is provided for dissipating the rest energy, and a solution becomes possible again (see right figure below).

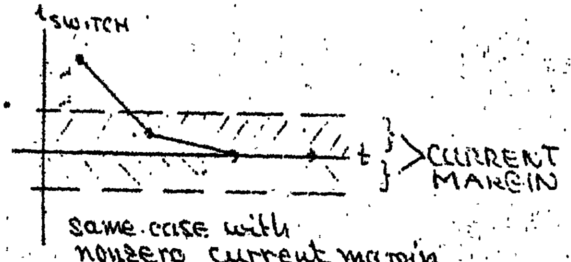




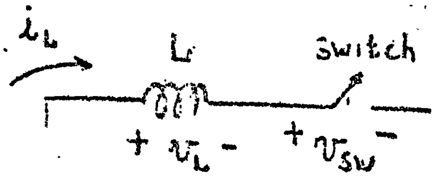
With CURRENT MARGIN = 0, the switch will open as soon as i_{SWITCH} changes its sign. Since the value of the current might be larger in the step where the sign change is noticed as compared with the value in the preceding step, it is advisable to use a non-zero current margin. See figures below.



zero current margin



same case with nonzero current margin



Added later insight (circa November, 1975)

The above comments are true; nonzero switch current at the instant of opening *will* cause trouble. But the problem is far more fundamental. There will in fact be voltage oscillation even though the switch opening occurs exactly at a current zero. The problem is inherent to the trapezoidal rule of integration which is being used, as explained in Reference 8, Vol. IV, November 12, 1975. Using the present EMTP logic, there will *always* be a voltage oscillation when the current through a hanging inductor is interrupted. Decreasing "DELTAT" so as to decrease the "rest energy" will *not* solve this problem.

$$\overset{0}{\cancel{i_L(t)}} = \overset{0}{\cancel{i_L(t-\Delta t)}} + \frac{1}{L}\cdot\int_{t-\Delta t}^{t} v_L(\tau)\,d\tau \qquad (1)$$

or

$$\frac{1}{L}\left(\frac{v_L(t-\Delta t)+v_L(t)}{2}\right)\Delta t = 0 \implies \boxed{v_L(t) = -v_L(t-\Delta t)} \qquad (2)$$

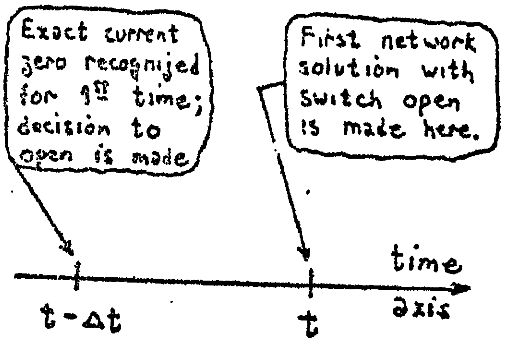

Exact current zero recognized for 1st time; decision to open is made
First network solution with switch open is made here.
time axis
t-Δt
t

Fig. 6. Assumed switch opening schedule.

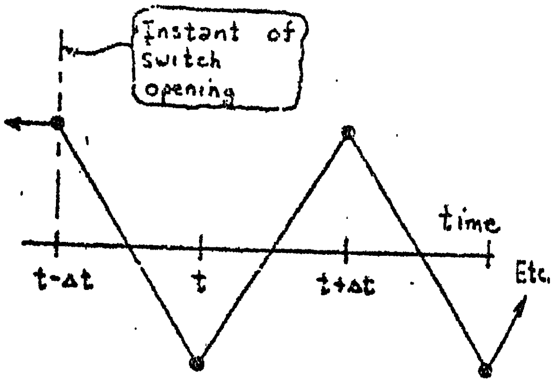


Fig. 7. Inductor voltage v_L for Figs. 5 and 6.

d) REMARK ON DELAY IN CLOSING ACTION OF SWITCHES

Except for a complication to be explained shortly, switch closing occurs as one would expect. When the program prints a message that a switch is closed after T seconds (see Fig. 1), it means that the closing occurs precisely at time $t = T$. For most cases, then, this is simple.

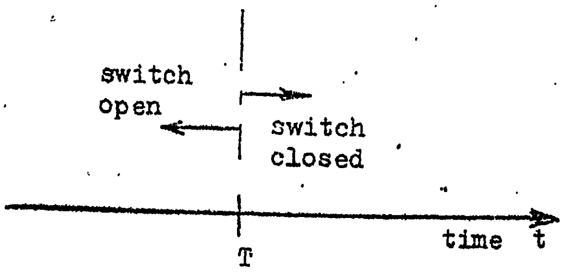


Fig. 1. Closing of switch at time instant $t = T$.

But a 1-step delay may actually occur in certain cases. A switch closing represents a change in the network; certain conditions (voltages, for example) immediately following the closure may be quite different than those immediately preceding the closure. In Fig. 1, we really should (ideally) get a network solution for $t = T+$, then. Among other things, this would clearly equalize the node voltages across the switch in question, and hence perhaps thereby initiate other flashovers which should also really be performed at time instant $t = T+$. But *the program does not presently perform such extra solutions in the same time step*. Equalization of node voltages for the just-closed switch will only occur as part of the network solution at time $T+\Delta t$, thereby introducing a delay of Δt.

Example

For the circuit of Fig. 2, with both the switch and type-99 (pseudo) nonlinear element open, no current flows. Hence source voltage $v_s(t)$ all appears across the switch, which will close when v_s exceeds flashover value V_{flash}^{sw}. At that instant the type-99 element should flashover too, assuming $V_{flash}^{99} < V_{flash}^{sw}$. But with present program logic, one time step would separate these two events.

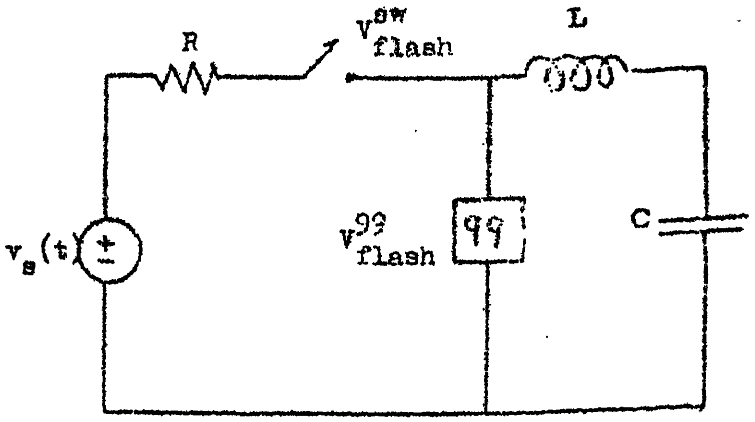
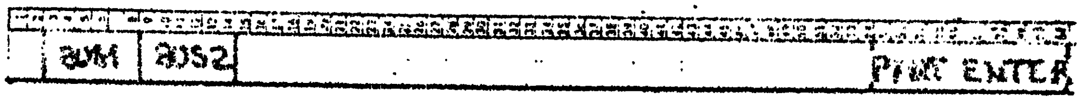


Fig. 2. Example illustrating delay.

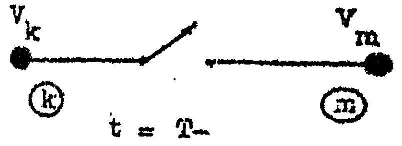
"PART ENTER" option for switch

A partial solution to the above problem, to be used only with extreme care, is provided by the PART ENTER feature. By punching these 10 characters in columns 55-64 of the switch card for a flashover switch, the following special action will occur:

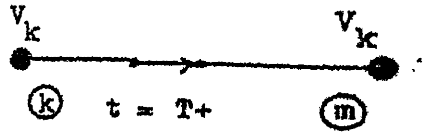
Action 1: Upon closure of such a switch, the node voltage of node BUS2 (data card field of columns 9-14) is set equal to the present value which exists for BUS1 (data card field of columns 3-8).



Action 2: This modified node voltage is then used in checking the status of all type-99 pseudo-nonlinear elements. It is also used for checking other flashover switches —— provided (if and only if) such other switches were inputted after the original switch which has closed. By "after," we are talking about order of data input.



(a) Before closure



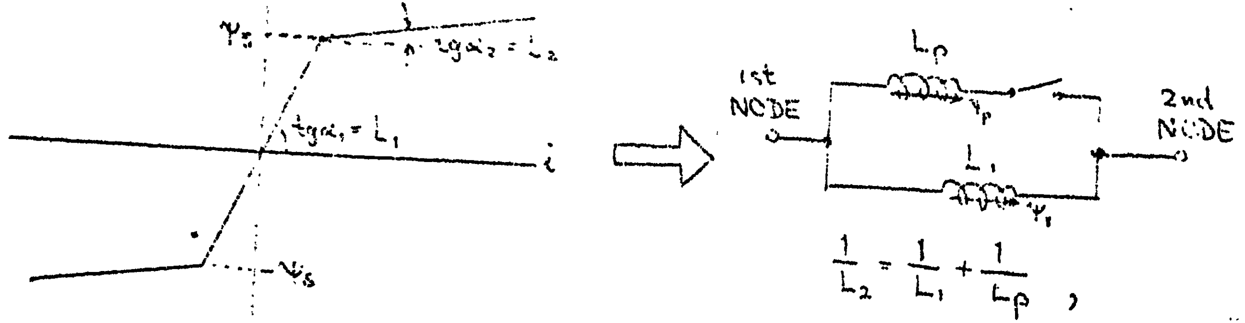
(b) After closure

Fig. 3. Illustration of voltage transfer due to PART ENTER feature of flashover switch.

1.41 SWITCHED-INDUCTANCE ELEMENT (Type 93)

General comment: The Type-93 switched-inductance element of this section was developed before the Type-98 pseudo-nonlinear reactor of Section 1.29 . Although the former has been retained in the EMTP, the Type-98 pseudo-nonlinear branch is used almost exclusively now at BPA. The one important exception is where residual flux is required (not presently allowed with the Type-98 element).

Used to represent a nonlinear inductance with two slopes L_1 and L_2 with a special parallel connection of two linear inductances, with the switch being closed in the saturated region and open in the unsaturated region. The flux in L_p is always computed from $\psi = \psi(0) + \int(v_{node1} - v_{node2})dt$ independent of the switch position. Therefore, it will automatically reach $\pm\psi_s$ at the instant of switch closing.



$$\frac{1}{L_2} = \frac{1}{L_1} + \frac{1}{L_p} ,$$

and $\psi_p = \psi_1$ independent of switch position.

a) RULES

1) Punch 93 in col. 1-2. This is switch type-code "ITYPE" .
2) Specify 2 nodes by names. One of the nodes may be ground. This is the 2A6 information of columns 3-14 , fields "BUS1" and "BUS2" .
3) It is the "BUS2" node (the second name of the pair) which has the switch connected to it; the "BUS1" node does not (see the equivalent circuit above). If "BUS2" does not have a voltage source connected to it, then there must be no other switch connected to "BUS2" (see preceding Rule 2 for Ordinary Switches, Page 27b-4).
4) There are four floating-point data fields on the card:

ψ_r — Residual flux (flux in the inductor at time zero). Some of the maethematics and approximations involved in this usage are documented in Ref. 8, Vol. VIII, 24 August 1978, pages VRTR-23 through [illegible] .

L_1 or ωL_1, L_2 or ωL_2 — Inductances in mH or reactances in Ω (depending on miscellaneous data parameter "XOPT" (see Section 1.0h).

ψ_s in Vs — Saturation point ($\psi_s = 0$ leads to error message). This is instantaneous flux, not RMS flux. This is further explained in Section 1.33 , in the note which precedes the rules.

5) If the transients case starts from a non-zero ac steady-state condition, then L_1 (unsaturated region) will be used in the ac steady-state solution. The initial flux $\psi(0)$ is automatically set and listed in the output. If $|\psi(0)| > |\psi_s|$ then the following message is printed below the output for $\psi(0)$: "***WARNING. ASSUMPTION THAT AC STEADY STATE HAS FUNDAMENTAL FREQUENCY ONLY IS QUESTIONABLE WITH PRECEDING FLUX OUTSIDE LINEAR REGION."

6) If a case has switched inductances as well as switched resistances, then the switched inductances must come after the switched resistances in the data deck. Otherwise execution is stopped with an error message (as per Section 2.4).

7) If the switched-inductance element is not excited during the steady-state phasor solution for initial conditions, then the user may want to specify residual flux. This is to be punched in the data field of columns 15-24 . But what about polarity? By definition, this is

$$\psi_r = \int_{-\infty}^{0} v_{km}(\tau)\, d\tau$$

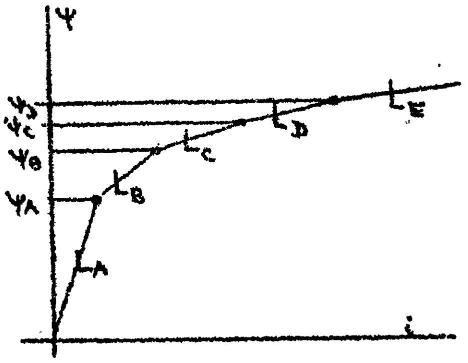
where v_{km} is the branch voltage drop from "BUS1" to "BUS2" (using notation $k \sim$ BUS1 , $m \sim$ BUS2 , $v_{km} = v_k - v_m$).

8) Output options for printing and/or plotting are punched in column 80, as follows:
   "1" punch is a request for switch current output;
   "2" punch is a request for switch voltage output;
   "3" punch is a request for both switch current and voltage output;
   "4" punch is a request for switch power and energy flow (see Section 1.8 for details).

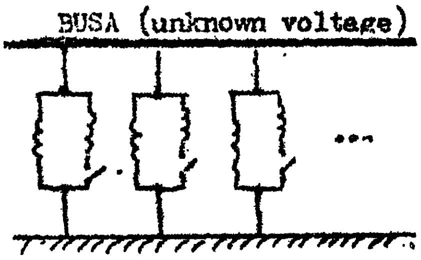
b) FORMAT

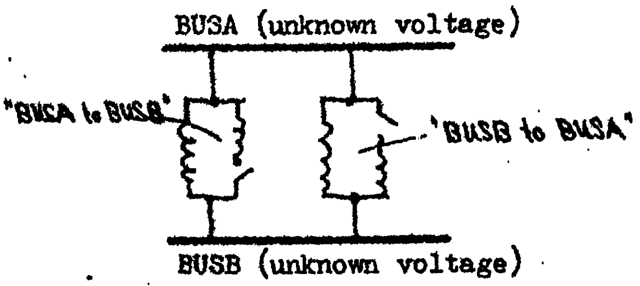
93	NODE NAMES		Residual flux ψ_r	L_1 in mH or ωL_1 in Ω	L_2 in mH or ωL_2 in Ω	ψ_s in (units of voltage)·s
	BUS1	BUS2				
I2	A6	A6	E10.6	E10.6	E10.6	E10.6

c) REPRESENTATION OF MORE THAN 2 SLOPES



Characteristics with more than 2 slopes can be simulated by connecting 2 or more switched inductances in parallel, provided that Rule 3 is not violated and that the total number of switches does not exceed its limit (List number 6 of variable-dimensioning; can be changed at will. Rule 3 does not pose any problem for switched inductances to ground if the second node name is "blank" (for ground), because ground may have any number of switches connected to it. If both nodes have unknown voltages, then only 2 switched inductances can be connected in parallel, but only if the pair of node names is reversed on the second card.





Any number permitted in parallel without violating Rule 3 if second node name is "   " for ground

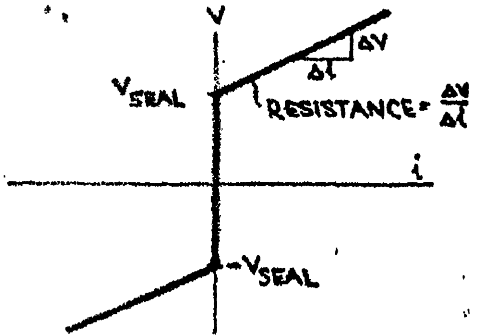
Only two permitted in parallel without violating Rule 3 ; the pairs of bus names must be in reverse order, note

Formulas for computing L_1 and L_2 (N switched inductances in parallel to represent slopes L_A, L_B, ...L_{N+1}):

	L_1	L_2	ψ_S
1st card	$\left.\begin{matrix} \\ \\ \\ \end{matrix}\right\} L_1 = N \cdot L_A$	$\frac{1}{L_{2(I)}} = \frac{1}{L_B} - \frac{1}{L_A} + \frac{1}{L_1}$	ψ_A
2nd card		$\frac{1}{L_{2(II)}} = \frac{1}{L_C} - \frac{1}{L_B} + \frac{1}{L_1}$	ψ_B
3rd card		$\frac{1}{L_{2(III)}} = \frac{1}{L_D} - \frac{1}{L_C} + \frac{1}{L_1}$	ψ_C
⋮			⋮
N-th card		$\frac{1}{L_{2(N)}} = \frac{1}{L_{N+1}} - \frac{1}{L_N} + \frac{1}{L_1}$	ψ_N

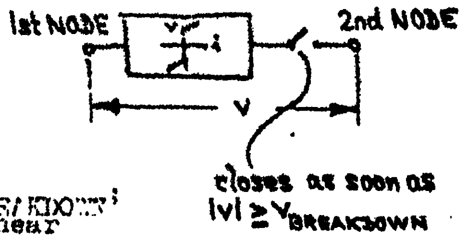
1.42 SWITCHED-RESISTANCE ELEMENT (Type 92)

General comment: The Type-92 switched-resistance element existed before the Type-99 pseudo-nonlinear resistive element of Section 1.28 . Although the former has been retained in the EMTP, the Type-99 pseudo-nonlinear branch is used almost exclusively now at BPA. For historical perspective, see Reference 8, Vol. I, October 13th, October 30th, and November 30th, 1973.



Used to simulate a nonlinear resistance or a lightning arrester with a characteristic of two slopes —— one infinite and one finite —— as shown at the right. After each clearing (current passing through zero), there is printout of the energy which has been absorbed (see Section 2.2c description).

Nonlinear resistance: Use $V_{BREAKDOWN} = 0$. More slopes are possible by connecting normal and/or switched resistances in parallel. No difficulty arises from such parallel connections, provided the second node name "BUS2" is blank (for ground). See Rule 3 below.



Lightning arrester: R is infinite until $|v| \geq V_{BREAKDOWN}$; thereafter, R is the value specified by the nonlinear characteristic. The lightning arrester will clear (R will become infinite) as soon as the current goes through zero. After the lightning arrester has cleared, breakdown will again occur as soon as $|v| \geq V_{BREAKDOWN}$, with subsequent clearing, etc. At this time it is not possible to connect more lightning arresters in parallel.

a) RULES

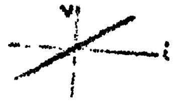
1) Punch $\boxed{92}$ in columns 1-2 . This is the switch type-code "ITYPE" .

2) Specify the two terminal nodes by name. One of the nodes may be ground (blank name field). This is the 2A6 information of columns 3-14 , fields "BUS1" and "BUS2" .

3) It is the "BUS2" node (the second node of the pair) which has the switch connected to it; the "BUS1" node does not (see the equivalent circuit above). If "BUS2" does not have a voltage source connected to it, then there must be no other switch connected to "BUS2" (see preceding Rule 2 for Ordinary Switches, Page 27b-4).

4) **Specify:** RESISTANCE in Ω. Note that the resistance is defined as the slope ΔV/ΔI of the nonlinear characteristic. This must be punched positive, though a near-zero, near-short-circuit value ε is permitted, if desired.

V_{SEAL}: The seal-off voltage, where resistance changes between finite and infinite value. V_{SEAL} must be punched positive, though a near-zero value ε is permitted.



$V_{BREAKDOWN}$: 0 for pure nonlinear resistance; breakdown voltage for lightning arrester, which will start conducting as soon as $|V| \geq V_{BREAKDOWN}$.

5) If the transients case starts from a non-zero ac steady-state condition, then R = ∞ will be used in the ac steady-state solution.

6) If a case has switched resistances as well as switched inductances, then the switched resistances must precede the switched inductances in the data deck. Otherwise execution is stopped with an error message (as per Section 2.4).

7) Output options for printing and/or plotting are punched in column 80, as follows:

"1" punch is a request for switch current output;
"2" punch is a request for switch voltage output;
"3" punch is a request for both switch current and voltage output;
"4" punch is a request for switch power and energy flow (see Section 1.8 for details).

8) For a lightning arrester the instance of discharge is printed as SWITCH '▨' TO '▨' CLOSED AFTER XXX SEC. The same message is also printed for the nonlinear resistance after current conduction starts as soon as $|v| \geq V_{SEAL}$. See Section 2.2c for details.

b) FORMAT

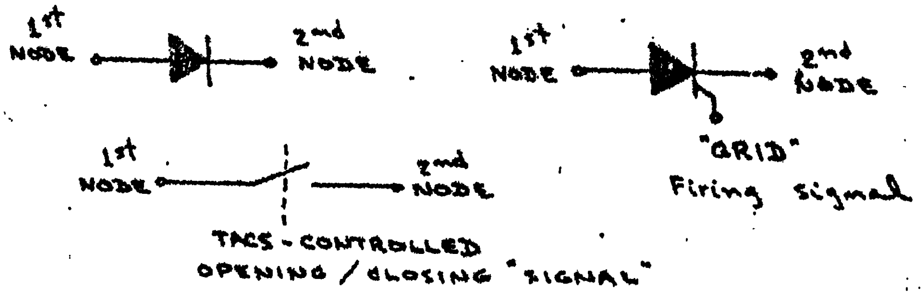
	NODE NAMES		RESISTANCE in Ω	▨	V_{SEAL} in units of voltage	$V_{BREAKDOWN}$ in units of voltage	80
2	BUS1	BUS2					
	A6	A6	E 10.6		E 10.6	E 10.6	I1

1.43 TACS-CONTROLLED SWITCH TYPE-11 FOR DIODE AND VALVE APPLICATION

Used to simulate a switch which, while following the simple opening/closing rules of a standard diode, may simultaneously be controlled by any given TACS variable used as:

- a grid firing signal
- or an overriding OPEN/CLOSE signal .

This type-11 switch may thus represent any of the following:



or a combination of any of those three modes, in which case either or both grid signal and overriding signal can simultaneously be active.

Besides the four alphanumeric node- and variable-names (used to define 1st-NODE, 2nd-NODE, and possibly — but not necessarily — "GRID" signal and "OPEN/CLOSE" signal) , three additional parameters may be defined:

- the minimum ignition voltage (V_{ig}), defaulted to 0.0
- the minimum holding current (I_{HOLD}), defaulted to 0.0
- the de-ionization time (t_{DEION}), defaulted to 0.0 .

a) RULES

1) Punch $\boxed{11}$ in columns 1-2 .

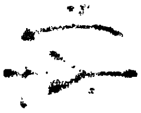
2) Specify the two terminal nodes by names (fields BUS1 and BUS2 of columns 3-14) . One of the nodes may be ground, indicated by a blank field. The direction of the current is taken to be from "BUS1" to "BUS2" . In other words, we have:

$$\left.\begin{array}{l}\text{anode — always "BUS1"}\\ \text{cathode — always "BUS2"}\end{array}\right\}\text{ for valves or diodes}$$

3) Remember that any node of unknown voltage can have at most one switch connected to it In this respect, the Type-11 switch (diode, valve, etc.) is no different than any other switch.

4) TACS grid signal and OPEN/CLOSE signal

○ If neither is specified, then the switch is a diode;



: the diode starts conducting when the forward voltage across its terminals becomes greater than the minimum ignition voltage V_{ig} (defaulted to zero)

: the diode ceases conducting as soon as the forward current becomes smaller than the minimum holding current I_{HOLD} (which is defaulted to zero)

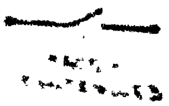
○ If the grid signal is specified (identified by the alphanumeric TACS-variable name in columns 65-70), then the switch is a valve

: which follows the opening and closing rules of the diode,

: except that the closing operation (start of conduction) will not take place until the value of the grid signal becomes greater than zero;

: unless the valve is actually reclosing within the de-ionization time following the previous opening, in which case the reclosing is immediate, with or without the presence of a valid grid signal. (Note that t_{DEION} is defaulted to zero.)

○ If the OPEN/CLOSE signal is specified (identified by the alphanumeric TACS-variable name in columns 71-76) , then the operating rules of the diode or the valve are overriden as soon as this signal becomes different than zero;



: if positive, the switch will immediately close and stay closed as long as the positive signal is active;

: if negative, the switch will immediately open and stay open as long as the negative signal is active;

: if zero, the switch returns to its regular diode or valve operating mode.

5) The switch may be specified as closed during the program-calculated steady-state initialization, if the user punches the keyword "CLOSED" in columns 55-60 .

6) To facilitate the punching of cards, the user may use the option "SAME" (by punching the keyword "SAME" in columns 61-64), when data for the parametric fields (V_{ig}, I_{HOLD}, and t_{DEION}) have to be repeated on one or more cards that are placed immediately after the card bearing the definition of these parameters.

7) The user may obtain a printed echo of the occurrence of all opening and closing operations of the switch, by punching a "1" in column 79 . (No such diagnostic if left blank or zero.)

8) Output options for printing and/or plotting:

Punch "1" in column 80 to get switch current,
" "2" " " " switch voltage,
" "3" " " " both current and voltage,
" "4" " " " switch power and energy flow.
(See Section 1.8)

b) FORMAT

	NODE NAMES									TACS NAMES		
11	BUS1	BUS2	V_{ig}	[illegible]	[illegible]		CLOSED	SAME	GRID	OPEN/ CLOSE		
I2	A6	A6	E10.0	E10.0	E10.0		A6	A4	A6	A6		

c) Samples of typical switch specification

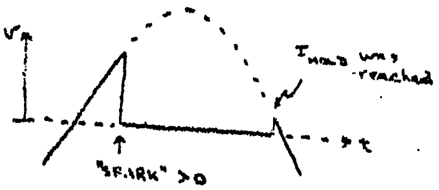
```
11L2    R2                                                 CLOSED
11LEFT  RIGHT                                                        FIRE2              1
11NODE1 NODE2                                                              ORDER
11L6    R6                                                           DELAY TRIG
```

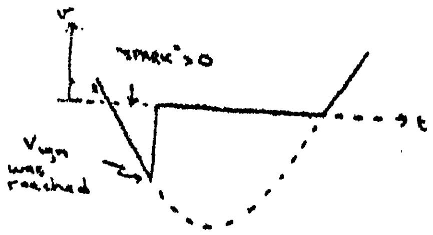
1. Diode from 'L2' to 'R2', conducting in steady-state.
2. Valve from 'LEFT' to 'RIGHT', with 'FIRE2' as grid signal from TACS . Every change of status will be echoed in the printout.
3. TACS-controlled switch from 'NODE1' to 'NODE2', operating as a diode when 'ORDER' has the value " 0.0 " .
4. Valve from 'L6' to 'R6', with grid signal 'DELAY', with its operation overriden by the TACS-variable 'TRIG' during the periods in which the value of 'TRIG' is different than zero.

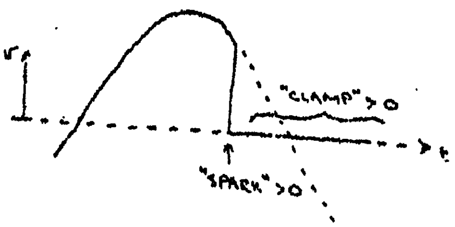
1.44 TACS-CONTROLLED SWITCH TYPE-12 FOR SPARK GAP AND TRIAC APPLICATION

Used to simulate a spark gap or a triac, with firing controlled by a TACS variable.

OPERATION







Opening/Closing Logic

- "CLAMP" signal from TACS
  - undefined → depends on "SPARK" signal
  - defined
    - $= 0$ → depends on "SPARK" signal
    - < 0
      - if closed → OPEN
      - if open → maintain open
    - > 0
      - if closed → maintain closed
      - if open → CLOSE
- "SPARK" signal from TACS
  - undefined → maintain open
  - defined
    - ≤ 0
      - if open → maintain open
      - if closed → depends on current
    - > 0
      - if open
        - if $v < V_{ign}$ maintain open
        - if $v > V_{ign}$ CLOSE
      - if closed → maintain closed
- current opening rules
  - $i > I_{hold}$ → maintain closed
  - $i < I_{hold}$ → OPEN

RULES

1) Punch 12 in columns 1-2 .

2) Specify the two terminal nodes by name (fields BUS1 and BUS2 of columns 3-14). One of the nodes may be ground, indicated by a blank field. The direction of the current is taken to be from "BUS1" to "BUS2" . Note that the opening current rules observe the absolute value of the current, not the polarity.

3) Remember that any node of known voltage can have at most one switch connected to it. In this respect, the type-12 switch is no different than any other switch.

4) Minimum ignition voltage: columns 15-24 , defaulted to 0.0

Minimum holding current : columns 25-34 , defaulted to 0.0

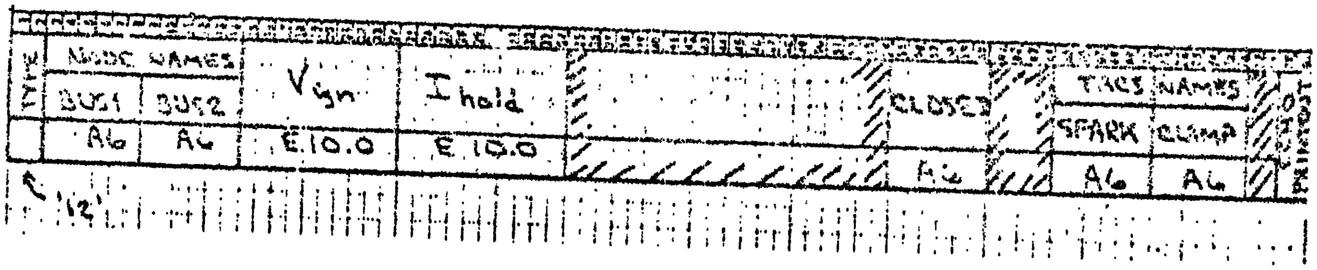
5) The switch may be specified as closed during the program-calculated steady-state initialization, if the user punches the keyword "CLOSED" in columns 55-60 .

6) The user may obtain a printed echo of the occurrence of all opening and closing operations of the switch, by punching a '1' in column [illegible] . (No such diagnostic if left blank or zero.)

7) Output options for printing and/or plotting:

Punch "1" in column 80 to get switch current
"2" switch voltage
"3" both current and voltage
"4" switch power and energy flow
(see Section 1.8)

FORMAT



1.45 SIMPLE TACS-CONTROLLED SWITCH TYPE-13

This type is used to represent a switch which is controlled by any given TACS variable.

The opening and closing operations are controlled by a single OPEN/CLOSE signal defined in columns 71-76 .

Comparison of switch type-11 type-12 and type-13

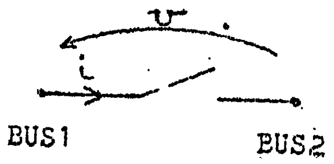
OPEN/CLOSE signal	type-11	type-12	type-13
< 0	OPEN	OPEN	OPEN
= 0	depends on GRID signal	depends on SPARK signal	OPEN
> 0	CLOSE	CLOSE	CLOSE

a) RULES

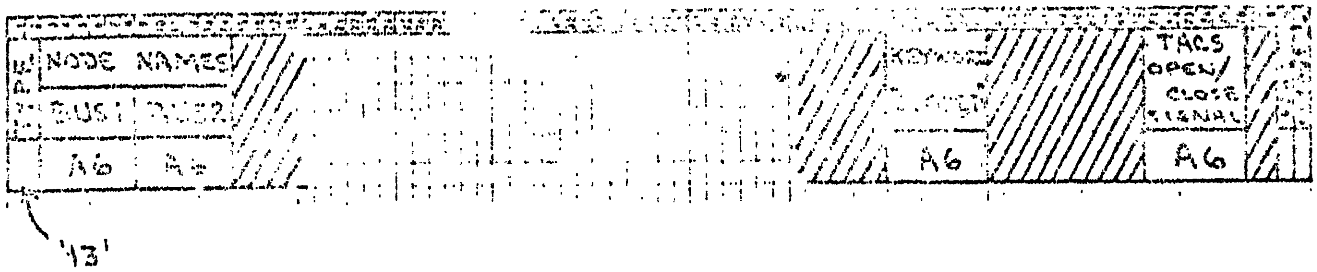
1) Punch $\boxed{13}$ in columns 1-2 .
2) Specify the two terminal nodes by name (A6 fields BUS1 and BUS2 of columns 3-14). One of the nodes may be ground (blank).
3) Remember that any node of unknown voltage can have at most one switch connected to it. In this respect, the type-12 switch is no different than any other switch.
4) The OPEN/CLOSE signal is identified by the TACS variable the name of which is punched in columns 71-76.
5) This switch is open during the program-calculated steady-state initialization at t = 0.0 , unless the keyword "CLOSED" is punched in columns 55-60 .
6) The user may obtain a printed echo of the occurrence of all opening and closing operations of this switch, by punching a "1" in column 79 . (No such diagnostic if col. 79 is left blank or zero.)
7) Output options for printing and/or plotting:

Punch "1"	in column 80 to get	switch current
"2"		switch voltage
"3"		both current and voltage
"4"		switch power and energy flow (see Section 1.8)

note:

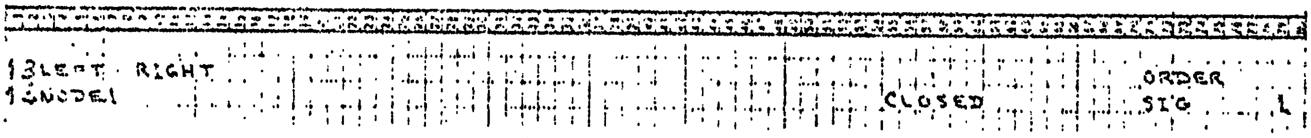


b) FORMAT



c) Sample of type-13 switch specification

1. Switch from 'LEFT' to 'RIGHT' controlled by the TACS variable 'ORDER' .
2. Switch from 'NODE1' to ground controlled by the TACS variable 'SIG' and closed at t ≤ 0.0 .



```
13LEFT  RIGHT                                                         ORDER
13NODE1                                               CLOSED          SIG      1
```

1.6 EMTP SOURCE COMPONENT DATA CARDS (SOURCE CARDS)

EMTP source components begin with conventional voltage and current sources which are analytic functions f(t) of time. One terminal of these must always be grounded (see Rule 9 for ways of circumventing this restriction). Normally the function f(t) can be chosen from a list of built-in function types, in which case the defining parameters are specified on the single source card. Up to ten functions of an arbitrary type can also be generated, as per Rule 4 immediately below. Finally, there are more complicated EMTP source components which have built-in differential equations (e.g., the 3-phase dynamic synchronous machine of Section 1.62).

If sinusoidal sources are active before the transient phenomena start (indicated by TSTART<0), then the program will automatically pre-compute the correct ac steady-state conditions and use these as initial conditions (see rule 5).

RULES:

(Associated format with examples on page 34)

1) Specify the source by the name of the node to which it is connected (source is always from node to ground). See Rule 9 for non-grounded source.

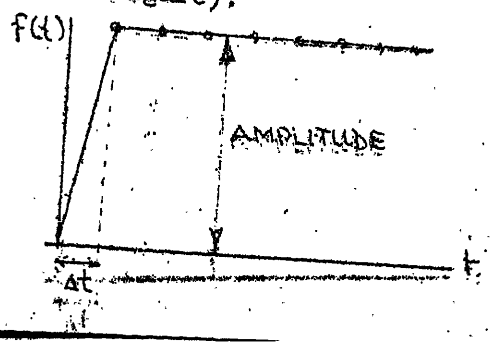
2) Indicate a voltage source by punching a non-negative integer (≥ 0 or blank) in columns 9-10.
Indicate a current source by punching a negative integer (<0) in columns 9-10 (current is measured into node).

4) The parameter TYPE specifies the type of the source function f(t) [e(t) = f(t) for a voltage source, i(t) = f(t) for a current source]. All functions f(t) are evaluated or read in at the discrete points t = 0, Δt, 2Δt,... only; linear interpolation is assumed in between.

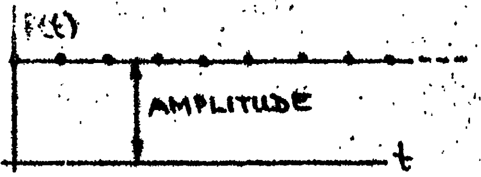
TYPE = 1,...,10: Up to 10 user-defined source functions f(t) are possible, associated with source-type numbers 1 through 10. Here f(t) are to be defined either empirically (one data card for every time step), or using the modeling of TACS, or in FORTRAN by means of a user-supplied subroutine "ANALYT". Details are covered in Section 1.9. Should only control by TACS be desired, use of Type 60-99 provides an alternative.

TYPE = 11: f(t) = AMPLITUDE, which is an approximate step function in the case of zero initial condition f(0) = 0 or a dc source in the case of initial condition f(0) = AMPLITUDE.

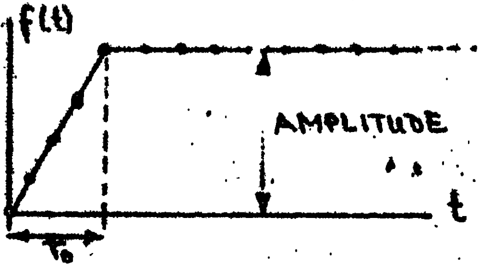
The step function is approximate in the sense that linear interpolation between discrete points produces a finite rise time Δt (see figure).



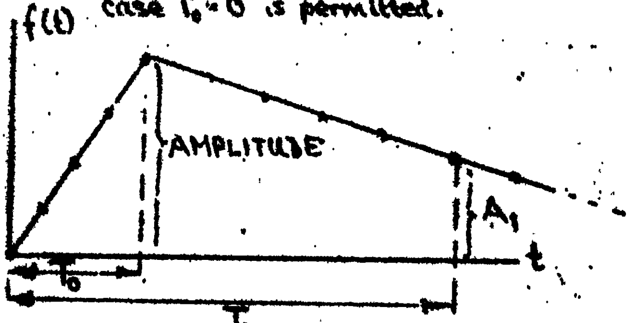
If initial condition f(0) = AMPLITUDE, then this type is a dc source (see figure).

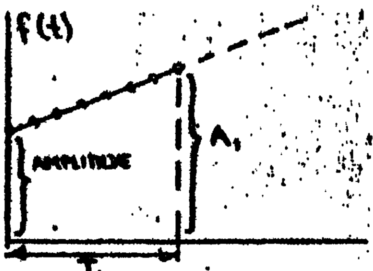


TYPE = 12: Ramp function with linear rise from t = 0 to t = To and constant amplitude thereafter (see figure, drawn for f(0) = 0).



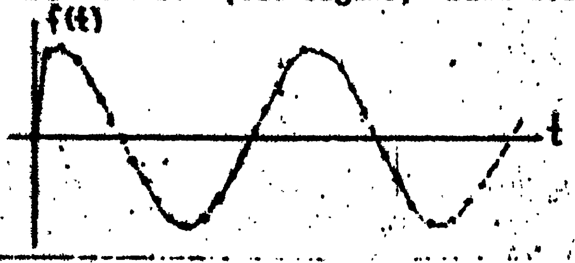
TYPE = 13: Ramp function with linear decay (see figure, drawn for f(0) = 0) or with linear rise if A_1 > AMPLITUDE. The special case $T_0 = 0$ is permitted.





Special case with $T_0 = 0$.

TYPE = 14: Sinusoidal function (see figure, drawn for f(0) = 0).



Two options are available. If

$A_1 = 0$: f(t) = AMPLITUDE * cos $(2\pi f \cdot t + \phi_o)$
with f = FREQUENCY .
ϕ_o in degrees

$A_1 > 0$: f(t) = AMPLITUDE * cos$[2\pi f(t + To)]$
with f = FREQUENCY
To in seconds.

Note: For consistency, the user should specify all sinusoidal amplitudes as peak rather than as RMS values. Unless this is done, the power flow and loss figures of the complete steady-state phasor solution printout (see Section 1.0h ; "KSSOUT" punched as "1" in column 32 of the integer misc. data card) will be only half of the correct values.

TYPE = 15 : Surge function $f(t) = \mathrm{AMPLITUDE} * (e^{\alpha t} - e^{\beta t})$
Note that α and β are usually negative.

TYPE = 16 : Special simplified representation of dc converter, as seen from the ac side. See Section 1.61 for details.

TYPE = 17 : Current source which approximates the performance of a zinc-oxide surge arrester, as fully documented in the EMTP memo dated July 30, 1976 (Vol V, Ref. 9). The source current depends upon the node voltage at the preceding time-step, as per:

$$i(t) = -A * (v / v_{ref})^G$$

The three arrester parameters are all positive; punch "A" in columns 11-20, "G" in columns 21-30, and v_{ref} in columns 31-40. Columns 9-10 and 41-59 are unused.

Note : As of late 1979, this Type-17 source is no longer recommended for usage in the average study. The representation of Section 1.32 is almost always to be prefered (thereby avoiding the one time step of delay, which can produce error, or instability).

TYPE = 19 : Request card which announces that all universal machine (U.M.) data cards for this data case follow. The rest of the data card (cols. 3-80) can be blank. See Section 1.63 for documentation of the U.M. data.

TYPE = 50
51
etc. :

Three-phase dynamic synchronous machine component, the data format and details of which are fully documented in Section 1.62 .

TYPE = 60
61
etc. :

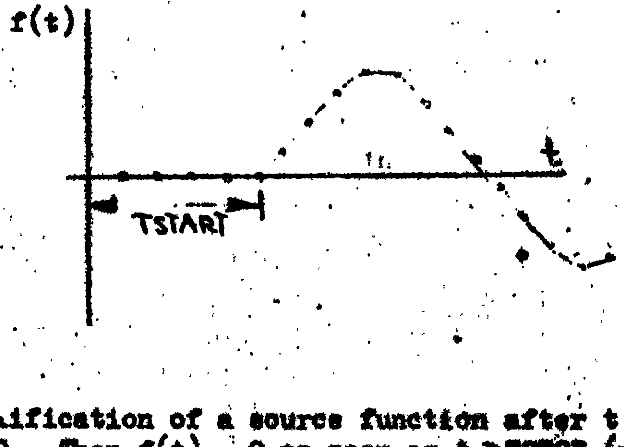
These are special source numbers, reserved for connection to (control by) TACS variables. TACS dynamics are fully described in Section 8. . Source values are automatically set equal to the TACS variables having the same 6-character names. Columns 11-60 of the source card are not used, and can be left blank. Type codes 60 through 99 allow for up to 40 such TACS-controlled electric-network sources.

Unlike the TACS control of Type 1-10 EMTP sources (see Section 1.9a), here the interface is established automatically; there is no need for any specification like the "TACS EMTP SOURCES" card of Section 1.0g2 . On the other hand, the Type 1-10 sources are somewhat more flexible (note in particular that the controlling TACS variables could have arbitrary names, for Type 1-10 sources).

5) Sinusoidal ac steady-state conditions are automatically computed as initial conditions for the transient phenomena. Simply punch TSTART < 0 on all source cards of TYPE 14 which are active in the steady-state. Note that only sinusoidal functions (TYPE 14) are considered as potential steady-state sources. The first source card encountered with TYPE = 14 and TSTART < 0 will determine the steady-state frequency f_{ac}; all other sources with TYPE = 14 and TSTART < 0, whose frequency does not deviate from f_{ac} by more than one percent, will also be included in the steady-state solution (with their frequency set to f_{ac}).

If steady-state conditions are desired for dc, treat dc as a sinusoidal function with very low frequency ($f(t) = \cos 2\pi ft$ with f very low) or read in initial conditions (section 1.7). See footnote on p. 35.

6) For a delayed start of a source function, use TSTART > 0. Then $f(t) = 0$ for $t <$ TSTART (not disconnected) and $f(t)$ as specified as soon as $t \geq$ TSTART. Note that the time count for the source function starts with TSTART (see figure) if TSTART > 0. Negative TSTART is set to 0 by the program, except for TYPE 14 where it is used to indicate steady-state sources with the time count starting at $t = 0$.

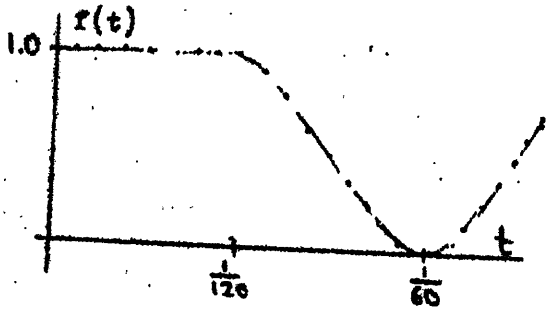


TSTART > 0
TYPE = 14
$A_1 = 0$ and $\phi_0 = -90°$
(makes it a sine-function)

7) For nullification of a source function after $t >$ TSTOP use the appropriate TSTOP > 0. Then $f(t) = 0$ as soon as $t \geq$ TSTOP (not disconnected). TSTOP = 0 or blank will be interpreted to mean TSTOP = infinity.

8) Composite functions, which are composed of pieces of available function types, can be produced by using TSTART and TSTOP.

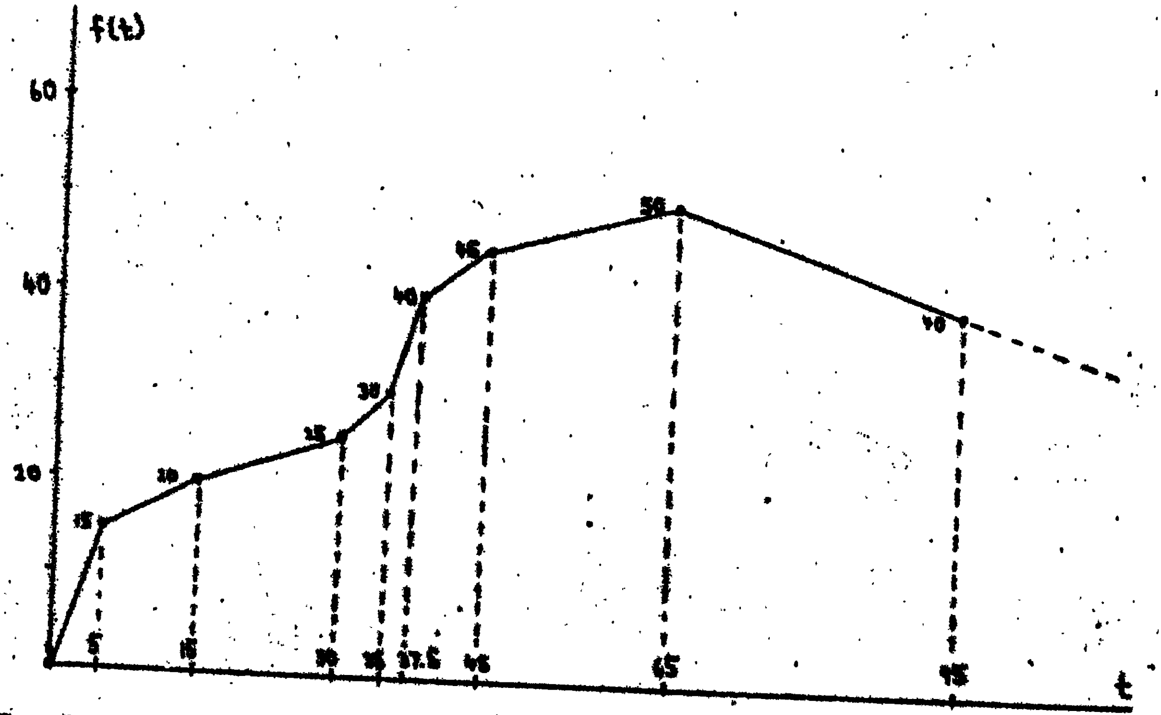
Example:



initial condition f(t) = 1.0
Three source cards:
1st card: TYPE = 11, AMPLITUDE = 1.0 TSTART=0
TSTOP = 1/120
2nd card: TYPE = 11, AMPLITUDE=0.5, TSTART=$\frac{1}{120}$
TSTOP=blank
3rd card: TYPE = 14, AMPLITUDE = 0.5,
FREQUENCY = 60, A_1=0, ϕ_0 = 0,
TSTART = 1/120, TSTOP = blank

Source type 13 with the appropriate parameters TSTART and TSTOP can be used to simulate piece-wise linear functions:

Example:

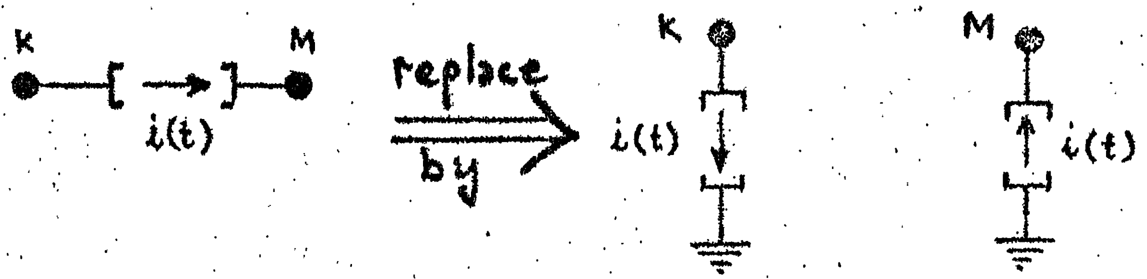


Use 7 source cards (first 2 slopes are simulated with one card):

	TYPE	AMPLITUDE	T_0	A_1	T_1	TSTART	TSTOP
1st card:	13	15	5	20	15	0	15
2nd card:	13	20	0	25	15	15	30
3rd card:	13	25	0	30	5	30	35
4th card:	13	30	C	40	2.5	35	37.5
5th card:	13	40	0	45	7.5	37.5	45
6th card:	13	45	0	50	20	45	65
7th card:	13	50	0	40	30	65	"blank"

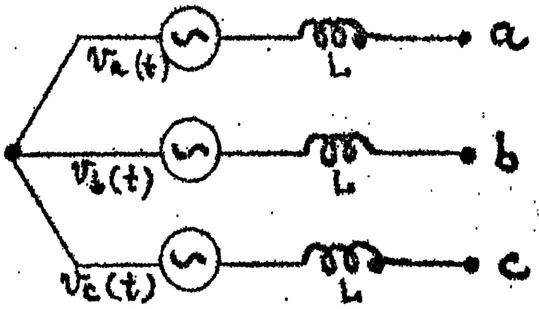
9) For sources which are not grounded at one end, two tricks are available, as follows:

a) Current sources require only a duplication, with the desired source from k to m replaced by one from k to ground and a second one from m to ground:

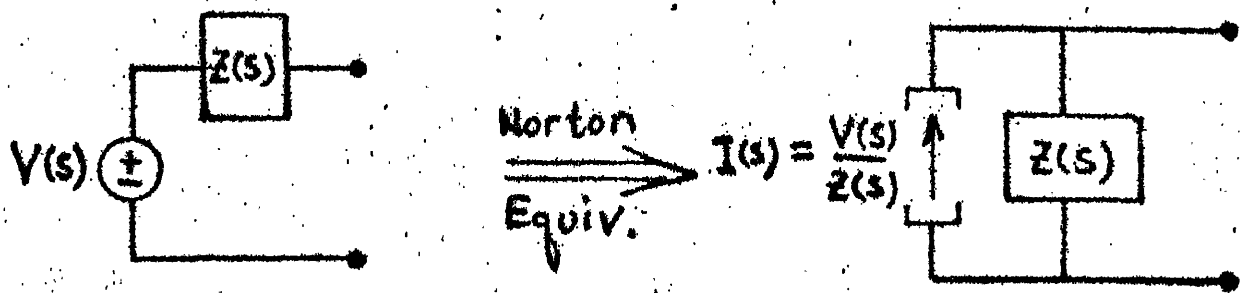


b) Voltage sources can be handled by first converting to equivalent current sources, provided that the voltage sources have some series impedance (which will always be true, physically). This amounts to finding the Norton equivalent of the original voltage source and impedance. Having done this, the current source in question is handled as per Point a) above.

Example: Consider the modelling of a 3-phase generator which is Wye-connected, but ungrounded, as per the sketch. Decoupled series source inductances $L \neq 0$ are assumed. The Norton equivalent of each phase is then found symbolically as follows, using Laplace transforms:



Wye-connected generator



Assuming $v(t) = V_o \sin(\omega t)$ for concreteness, we have the following calculations: $V(S) = \omega V_o / (S^2 + \omega^2)$

$Z(S) = SL$, so

$$I(S) = \frac{V_o}{\omega L}\left[\frac{\omega^2}{S(S^2+\omega^2)}\right] = \frac{V_o}{\omega L}\mathcal{L}\{1 - \cos\omega t\}$$

$$i(t) = \frac{V_o}{\omega L} - \frac{V_o}{\omega L}\cos\omega t$$

TYPE	NODE NAME	VOLTAGE OR CURRENT?	AMPLITUDE (ignored for type=1...10)	FREQUENCY in HZ (ignored if nottype ≠ 14) or α for type #15	T_0 in s or Φ_0 in degrees (ignored if type=1...11) or β for type #16	A_1 (ignored if not type ≠ 13 or 14)	T_1 in s (ignored if not type ≠ 13)	TSTART in s (ignored if type=1...10)	TSTOP in s (ignored if type=1...10)
I2	A6	I2	E 10.6	E 10.6	E 10.6	E 10.6	E 10.6	E 10.6	E 10.6
7	BUS-1								
10	BUS-2	-1							
11	BUS-3	-1	-.5						
12	BUS-4		.8		.05				
14	BUS-5		1.2	60.	-.06				
13	BUS-6		1.		1.0E-6	0.5	50.0E-6	-1.	50.0E-6

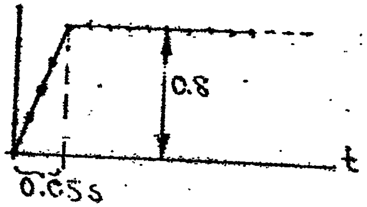
EXAMPLES:

BUS-1 is a node with voltage excitation whose value is read in from cards as the 7th value (columns 57-64) on the card,

BUS-2 is a node with current injection whose value is read in from cards as the 10th value (columns 73-80) on the card,

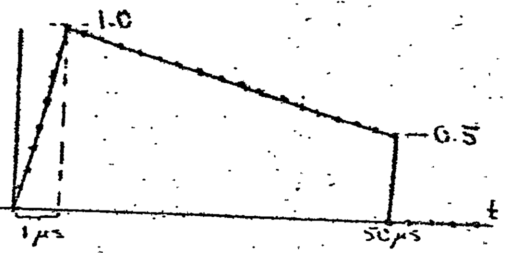
BUS-3 is a node with current injection i(t) = -0.5

BUS-4 is a node with voltage excitation of the following form:



BUS-5 is a node with voltage excitation, present in the steady state and thereafter, e(t) = 1.2 cos (2π60t-0.06)

BUS-6 is a node with voltage excitation of the following form:

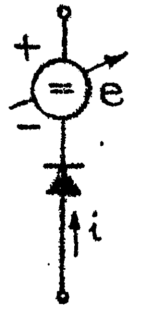


1.61 CONTROLLED D-C VOLTAGE-SOURCE

1-2	3-8	9-10	11-20	21-30	31-40	41-50	51-60	61-70	
TYPE	NODE NAME CATHODE SIDE	INITIAL	K	$e_{initial}$ if INITIAL=1 $e_{setting}$ if INITIAL=2 or 3	T_1 (s)	T_2 (s)	T_3 (s)	$i_{initial}$	
I2 16	A6	I2	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	
1-2	3-8	9-10	11-20	21-30	31-40	41-50	51-60		80
TYPE	NODE NAME ANODE SIDE	▨	k_1	k_2	e_{min}	e_{max}	R_e		IOUT
I2 16	A6	▨	E10.6	E10.6	E10.6	E10.6	E10.6		I1

To be used for a d-c voltage source which is controlled by its current output (simulation of HVDC terminals with ripples in the d-c voltage ignored).

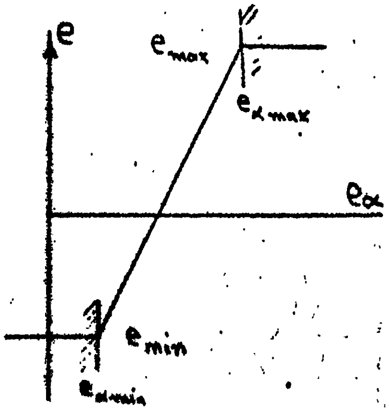
NODE NAME
CATHODE SIDE



NODE NAME
ANODE SIDE

Note that the d-c voltage source is not defined by its positive and negative terminals but by cathode and anode side. The positive direction of current flow is from anode to cathode. Current is not permitted to flow in the negative direction (this is simulated with a switch on the anode side).

The voltage e is a function of i as follows:



$$e = k_1 + k_2 e_\alpha \qquad (1)$$

and

$$e_\alpha = K(I_{BIAS} - i)\frac{1+sT_2}{(1+sT_1)(1+sT_3)} \qquad (2)$$

The steady-state limits on e,

$$e_{min} \le e \le e_{max}$$

are translated to limits on e_α with eq. (1). During transient conditions, the limits will be observed on e_α only. After $e_{\alpha\,max}$ or $e_{\alpha\,min}$ has been reached, or was there to start out with, backing off the limits takes place as soon as the value of the derivative

$$(T_1+T_3)\frac{de_\alpha}{dt} = K(I_{BIAS}-i) + KT_2\frac{d(I_{BIAS}-i)}{dt} - T_1T_3\frac{d^2e_\alpha}{dt^2} - e_\alpha \;; \qquad (3)$$

changes sign (turning from positive to negative in case of $e_\alpha = e_{\alpha\,max}$). The value for d^2e_α/dt^2 is set to zero in the right-hand side of Eq. (3) when e_α is at the limit.

RULES:

1) Specify the source by type 16 on 2 cards (first card with node name for cathode side and parameters INITIAL, K etc., second card with node name for anode side and parameters k_1, k_2, etc.).

3) The steady-state initial conditions are automatically computed, with the d-c voltage source simulated as $e = e(0)\cdot\cos\omega t$ with $\omega = 2\pi f$ and $f = 0.001$ Hz. If the initial conditions are to be zero, simply set $e(0) = 0$. Depending on the value of INITIAL,

$$e(0) = e_{INITIAL} \quad \text{if INITIAL} = 1$$
$$e(0) = e_{max} \quad \text{if " } = 2$$
$$e(0) = e_{min} \quad \text{if " } = 3$$

If the value of INITIAL is less than 1 or greater than 3, then an error message is printed "ERROR IN IDENTIFICATION OF SOURCE".

The initial current $i_{INITIAL}$ must be given by the user because the voltage source has an internal resistance in series in the transients program (its value is printed in the record of source date as EQUIV. RESISTANCE). This equivalent resistance results from the transformation of the differential equations to difference equations with the trapezoidal rule of integration. The program then sets $e_{SOURCE} = e(0) + R_{EQUIV}\cdot i_{INITIAL}$. If the initial current is wrong, then the initial voltage at the terminals will not be exactly $e(0)$; this error may or may not be negligible depending on whether $|R_{EQUIV}\cdot i_{INITIAL}| \ll |e(0)|$ or not. Note that $i_{INITIAL}$ is only used for the compensation just mentioned and for nothing else. If $i_{INITIAL} < 0$, then it is set to zero internally in the program.

4) The value I_{BIAS} in Eq. (2) is automatically computed after return from the steady-state subroutine. With e_{source} as defined in rule 3, the steady-state current $i(0)$ is automatically obtained. Note that this $i(0)$ may differ from $i_{INITIAL}$ if the latter was not given correctly, except if the user specifies $i_{INITIAL} = 0$. In this case, $i(0)$ will also be zero because the switch which simulates the diode effect would be kept open for the steady-state solution. I_{BIAS} is then computed from

$$e_{\alpha}(0) = K\cdot(I_{BIAS} - i(0)) \quad \text{if INITIAL} = 1, \tag{4}$$

or

$$e_{\alpha}(0) = K\cdot(I_{BIAS} - i_{SETTING}) \quad \text{if INITIAL} = 2 \text{ or } 3. \tag{5}$$

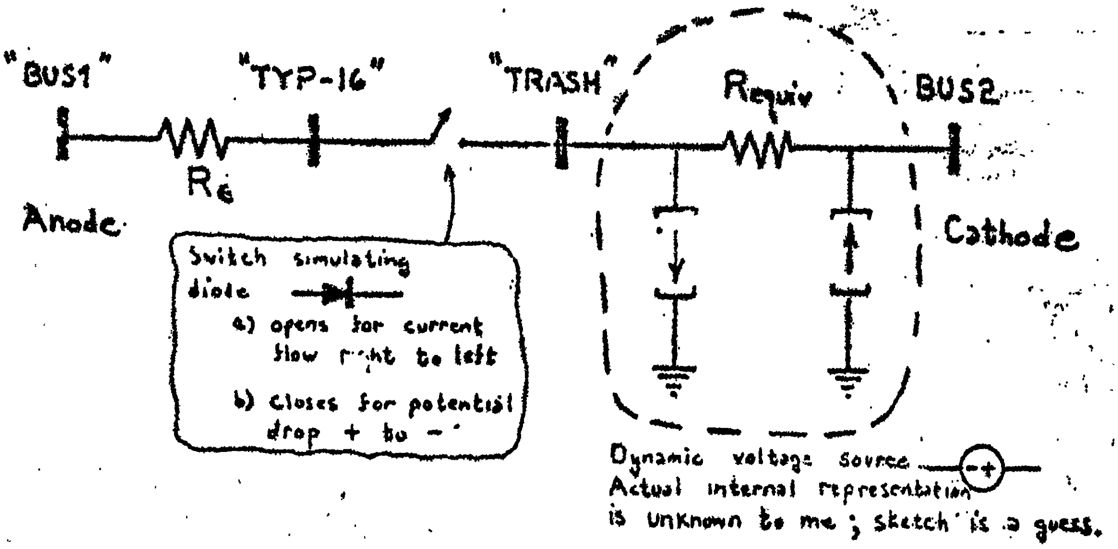
Eq. (5) is used if the steady-state voltage was at its minimum or maximum limit; in this case, the current setting $i_{SETTING}$ is assumed to be the value where the control would begin to back off the limit again.

5) Output options for [illegible]ating and/or plotting:

Punch "1" in col. 80 on card for ANODE side to get branch current,
"2" " to get branch voltage,
"3" " to get both.

6) Spurious voltage oscillations may occur at the terminal after current extinction unless damping circuits are also modeled. Dr. W. Long of Hughes Research Laboratories obtained good results by adding a RC branch between anode and cathode (R=900 Ω, C=0.15 µF). Bill is now (1977) with the University of Wisconsin in Madison, Dept. of Electrical & Computer Engineering.

7) Data field R_ϵ of columns 51-60 of the anode source card is used to specify the resistance in ohms of a small series isolation resistor which is defined internally by the program. In the following diagram showing internal EMTP representation of the type-16 source component, the resistor in question is that between the user-supplied anode node name "BUS1" and the internally-defined node "TYP-16" :


"BUS1"
"TYP-16"
"TRASH"
Requiv
BUS2
Rε
Anode
Cathode
Switch simulating diode
a) opens for current flow right to left
b) closes for potential drop + to -
Dynamic voltage source
Actual internal representation is unknown to me; sketch is a guess.

See the EMTP memorandum dated November 19, 1975 (Reference 8), as to the reason for this isolation branch. If field R_ϵ is left blank (or punched with the value 0.0), the EMTP will automatically supply a default value equal to the square root of "EPSILN", where "EPSILN" is a floating-point miscellaneous data parameter (see Section 1.0h). A column-80 (data field "IOUT") request for current output will be internally converted into a current-output request for resistor R_ϵ, and it will show up this way in the printed column headings which precede the transient printout; a column-80 request for branch-voltage output will produce the voltage difference from anode to cathode. Just as with the node name "......" which is internally generated by the EMTP for each switched-inductance or each switched-resistance element (see Section 1.4), use of the node name "TYP-16" should always be avoided by the user.

1.62 THREE-PHASE DYNAMIC SYNCHRONOUS MACHINE SOURCE COMPONENT

Before describing what is involved in this section, let me first briefly mention what is not involved. If the dynamics of Parks's equations are not wanted, power system generators are typically represented by sinusoidal voltage sources (Type-14 source of Section 1.6). If the rotating machine is not a conventional, balanced, three-phase synchronous generator, the user is referred to the universal machine (U.M.) modeling of Section 1.63 . The user might also consider the U.M. modeling if he requires more masses or more machines than the temporarily fixed dimensions of this present section allow (the U.M. code is fully variably-dimensioned, though some data setup is more laborious). The modeling of Section 1.62 is designed only for conventional synchronous power system generators which are not too numerous (limit as sent out from BPA is 4; see end of Section 1.62b), and for which the number of masses is reasonable (limit as sent out by BPA is 10 per machine).

There presently are two competing EMTP synchronous machine (S.M.) models in the EMTP. This is for the 3-phase case, with balanced armature windings --- the conventional case of interest for power system analysis. The models are:

a) Type-59 EMTP source modeling of Section 1.62a (the so-called Brandwajn modeling).
b) Type-50 (or 51, or 52, or 53) EMTP source modeling of Section 1.62b (the so-called SCE modeling).

A user must choose one or the other of the two; he can not mix the two models within the same EMTP data case.

The two S.M. modeling alternatives satisfy essentially the same user needs, and a competent user should be able to successfully model a given problem using either, in general. Further, data requirements of the two models are very similar, the connections to TACS are nearly the same, and outputs are comparable (though some units are different).

There are two ways in which Type-50 modeling is more flexible than Type-59 modeling. First, the Type-50 modeling allows for a delta connection of the armature windings, while Type-59 does not. But all known power system generators are Wye-connected. Second, the Type-50 modeling allows a choice between per unit and physical units for the output, while all Type-59 output is in physical units. If per unit output is important to the user, note this restriction of Type-59 modeling. The general view from program maintenance at BPA is that per unit input/output is a pain (there is an incredible amount of confusion), and that we would all be better off if everything was in absolute MKS units (e.g., meters rather than centimeters or kilometers, etc.). All Ontario Hydro S.M. usage is with Type-59 , using only physical units for output.

A fundamental difference between the two models is related to compensation: Type-50 modeling uses it, while Type-59 does not. This affects the user in that Type-50 dynamic S.M. busses must be separated by distributed-parameter transmission lines (to decouple the S.M. equations), while Type-59 S.M. busses need not. In fact, the user can connect an arbitrary number (within existing fixed-dimension limits) of Type-59 machines in parallel on the same bus. Thus the

Type-59 machine is generally easier to use, and is more flexible. It is also much more efficient computationally, for the average usage. Reference 8, Vol. VII, 23 December 1977, page CBVB-5 documents a speed-up ratio of 2.5 for the IEEE SSR Benchmark test case, when run on a CDC-6500 computer system.

After hearing such a comparative analysis, one might wonder why the Type-50 model is even made available to the user. I might offer some historical explanation, beginning with the recommendation that the user read of Dr. Vladimir Brandwajn's contribution to program development in Section 0.2 . The Type-50 model came first, and has been extensively used by the power industry (particularly electric utilities in the southwestern USA, where concern over SSR originated) between 1975 and 1980. It was the outgrowth of much hard work by Mike Hall and John Alms of SCE, in the aftermath of the Mohave shaft-bending accident. An effective, reliable, useful tool was developed by SCE, and after some massaging in Portland (see Ref. 8, 5 Dec 1976, Vol. VI, pagination FOTS), was made available to the non-IBM general public for the first time via "M21." translations. The corresponding EMTP User's Manual (now Reference Manual) was dated November, 1977, and it mentions only this modeling. As a result, all but a select few insiders have been using Type-50 S.M. modeling for shaft-torque problems until now (1980). Actually, the Type-59 S.M. code was present in the "M21." EMTP, but it still had bugs, and was then being actively developed by Vladimir. This work has continued, and Vladimir today reports that Ontario Hydro uses only the Type-59 modeling. He and his colleagues have used it for several years, and have yet to find a problem which can not be solved successfully using it. On the other hand, Vladimir reports that he does have a case which the Type-50 modeling can not handle (the iteration fails to converge, despite his knowledgable adjustment of parameters).

So where does EMTP S.M. model usage stand today? Based on the best available information (Ontario Hydro usage), the Type-59 model is believed to be generally preferable. It appears possible that within a year or two, a decision to remove the older Type-50 model might well be made, as part of industry-wide coordinated EMTP development. See Ref. 8, Vol. IX, 6 August 1979, page FYTM-15, Project 17. Users of the Type-50 S.M. modeling are thus being given notice of a possible furture discontinuity. They are encouraged to use the Type-59 model, and perform their own comparisons. If any realistic problem of practical industry importance can be found for which Type-50 modeling works satisfactorily but Type-59 modeling does not, the documentation should be communicated to Toronto and Portland. Vladimir has always been open-minded on the question, and naturally hesitant to recommend removal of the Type-50 code. But such a decision may well be forced on him in a year or a year and a half, as part of coordinated EMTP development. So, Type-50 model users, now is the time to come to the aid of your model, if you know something which we do not.

The general summary recommendation, then, is for all EMTP S.M. users to try the Type-59 modeling of Section 1.62a . The Type-50 S.M. model of Section 1.62b is considered to be alternative, backup modeling. Any documented evidence which might call this evaluation into question should be communicated to Ontario Hydro and BPA. Finally, be prepared for the possible removal of Type-50 modeling in the future. The user instructions have been separated for this reason, locking toward the future removal of Type-50 modeling, even though there is considerable duplication as a result (most material is identical).

1.62a TYPE-59 DYNAMIC SYNCHRONOUS MACHINE SOURCE COMPONENT

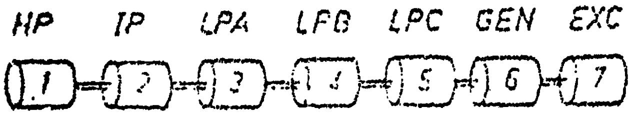


Fig. 3 Model of turbine-generator unit

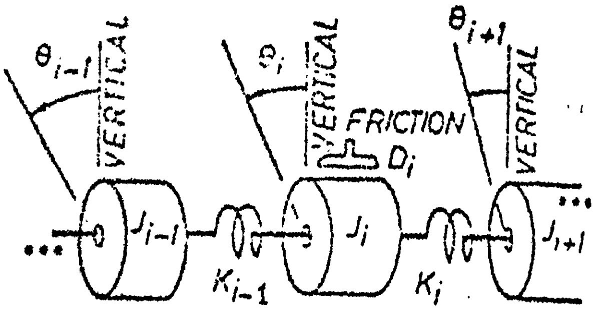
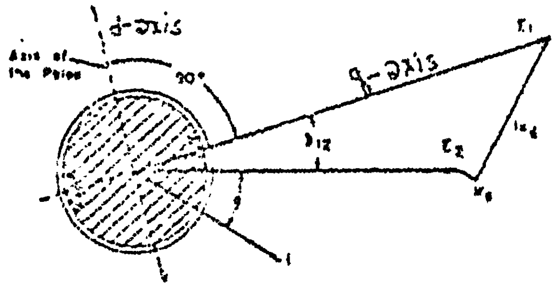


Fig. 4 Turbine-generator part around mass i



General Description of Component

Mathematics of the Type-59 dynamic synchronous machine source component (an EMTP source by general classification) were developed at the University of British Columbia in Vancouver as part of the doctor research of Dr. Vladimir Brandwajn, conducted under the supervision of Prof. Hermann W. Dommel. The theory is fully documented in Vladimir's Ph.D thesis (Ref. 15), and Ref. 20 provides a shorter summary. Actual implementation and enhancement in the EMTP was performed under contract with BPA, as documented in Ref. 8, Vol. VII, 23 December 1977, pagination CBVB.

The dynamics of Park's (Blondel's) equations are provided for, with a maximum of two rotor circuits on each axis. The mechanical side of the machine is modeled as an interconnection of masses and springs, plus viscous damping, thereby providing SSR (subsynchronous resonance) modeling capability. An arbitrary number of these Type-59 S.M. components can be connected in parallel at the same generator bus, and there is no need to isolate machines by distributed-parameter lines. Finally, arbitrary control system dynamics can be modeled using TACS (see Section 8.), and connected either to the shaft (for prime-mover dynamics) or the field circuit (for exciter dynamics).

Initialization of the dynamic synchronous machine (S.M.), meaning the assignment of state variables at the time the simulation begins (usually time zero), is based on the EMTP phasor (sinusoidal steady-state) network solution. For this purpose, the user specifies a voltage magnitude and angle for the terminal bus of phase "a" ; it is internally extended to phases "b" and "c" by the EMTP, using the assumption of balanced, positive-sequence operation. Upon completion of the phasor network solution, the injected currents are known. Positive and negative sequence components are then used for the S.M. initialization. For unbalanced networks, note that this involves an approximation. Further work on the unbalanced case is reported in Ref. 23.

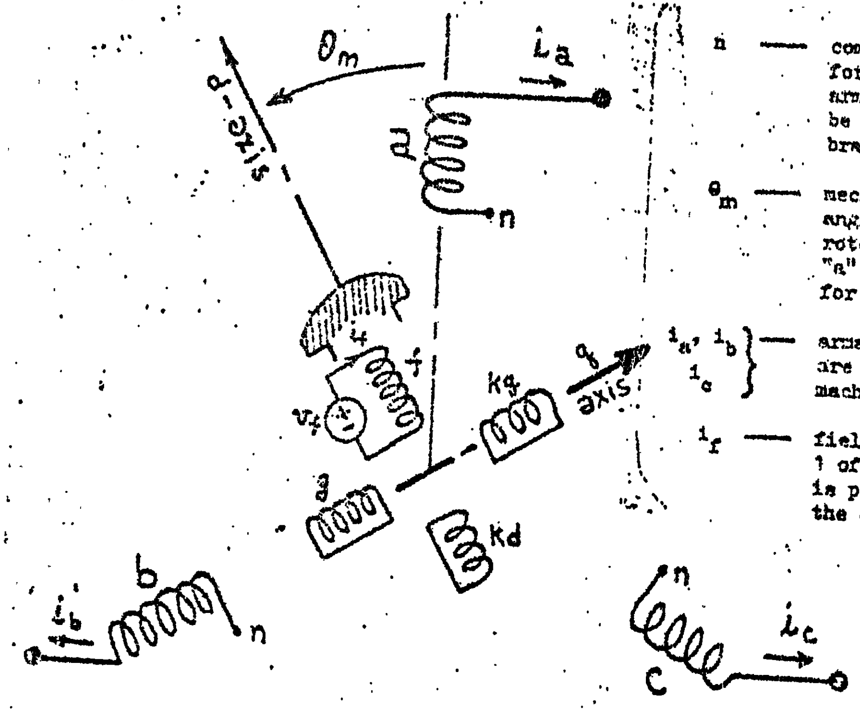
Should the user employ TACS for the representation of exciter dynamics, he must define the associated TACS initial conditions himself, manually. At this time, automatic initialization by the EMTP, based on the result of the machine initialization and the electric network solution, has not yet been worked out.

The dynamic S.M. component is internally balanced (with respect to the armature phases), and is inherently three-phase. The windings are assumed to be Wye-connected, with a possible R-L branch between the neutral and local ground.

For output purposes, most machine parameters of interest are available : velocities and angles of the rotor masses, inter-mass shaft torques, winding currents, and certain d-q-0 variables. Such output quantities are automatically appended to the end of the regular EMTP output vector upon the request of the user, and hence are available for printing and plotting just like any other EMTP variable.

Each rotor mass is allowed to have a constant mechanical power applied to it (in addition to the torque of mechanical viscous damping and the spring connection to adjacent masses). The user specifies proportionality factors for each mass, with the actual constant power then determined internally by the EMTP at the time of the sinusoidal steady-state initialization (so as to produce equilibrium). This is the basic scheme regarding mechanical input torque, in the absence of special connections. But the user is allowed to represent prime mover (e.g., governor, boiler, etc.) dynamics if he so chooses, by using TACS (see Section 8.) to control the just-described total mechanical power. In this case, the required TACS output variable is a normalized multiplicative constant (equal to unity if it is to produce no effect) for scaling the otherwise-constant mechanical power. Should the user desire a constant-torque representation of the prime mover, this can be readily provided by the TACS connection (TACS would divide the steady-state speed by the instantaneous speed to produce the required control signal).

Even without any detailed explanation of where they come from, it might be desirable to document the set of equations which is used to model the S.M. We have:



n —— common neutral connection point for the three Wye-connected armature windings. This point may be grounded through a series R-L branch.

θ_m —— mechanical angle of the rotor (the angle between the direct axis of the rotor and the axis of armature phase "a"). Sketch is for a 2-pole machine, for simplicity.

i_a, i_b, i_c —— armature currents. Note that these are positive when flowing out of the machine (generator convention).

i_f —— field current (current in winding number 1 of the direct axis of the rotor). This is positive into the coil, in accord with the direction of steady-state flow.

Counter-clockwise steady-state rotation:

$$\frac{d\theta_m}{dt} = -\left(\frac{2}{NP}\right) \cdot 2\pi\,\mathrm{FREQ}$$

f, kd —— rotor windings number 1 and 2 of the direct axis (d-axis), respectively.

g, kq —— rotor windings number 1 and 2 of the quadrature axis (q-axis), respectively.

Notes about mechanical equation (see lower right-hand corner of next page)

1) Coefficient names are as defined in the section about Class 4 S.M. data cards.
2) This equation is Newton's law in rotational form for mass number "k" , assuming the most general case.
3) If mass number "k" is not the generator rotor, omit the electromechanical torque T_{em} .
4) If mass number "k" is at one end of the shaft system, either mass number k-1 or mass number k+1 (or both, in the case of a single mass system) will not exist. In this case, the associated terms of mutual coupling ("DMUT" and "HKCO") are defined to be zero.
5) The synchronous mechanical frequency "f" enters only through the speed-deviation self-damping term.
6) As used here, Θ_k is the absolute angle of mass number "k" of the shaft system.
7) T_k^{mech} is the externally-applied mechanical torque on mass number "k" , in the direction of $+\Theta$.

$$v_d = -R_a i_d - \frac{d\lambda_d}{dt} - \lambda_q \frac{d\theta}{dt}$$

$$v_q = -R_a i_q - \frac{d\lambda_q}{dt} + \lambda_d \frac{d\theta}{dt}$$

$$v_o = -(R_a+3R_n)\, i_o - \frac{d\lambda_o}{dt}$$

$$v_f = -R_f i_f - \frac{d\lambda_f}{dt}$$

$$0 = -R_g i_g - \frac{d\lambda_g}{dt}$$

$$0 = -R_{kd} i_{kd} - \frac{d\lambda_{kd}}{dt}$$

$$0 = -R_{kq} i_{kq} - \frac{d\lambda_{kq}}{dt}$$

$$T_{en} = \frac{NP}{2}(\lambda_d i_q - \lambda_q i_d)$$

$$\begin{bmatrix} \lambda_d \\ \lambda_q \\ \lambda_o \\ \lambda_f \\ \lambda_g \\ \lambda_{kd} \\ \lambda_{kq} \end{bmatrix} = \begin{bmatrix} L_d & 0 & 0 & L_{af} & 0 & L_{akd} & 0 \\ 0 & L_q & 0 & 0 & L_{ag} & 0 & L_{akq} \\ 0 & 0 & L_o & 0 & 0 & 0 & 0 \\ L_{af} & 0 & 0 & L_f & 0 & L_{fkd} & 0 \\ 0 & L_{ag} & 0 & 0 & L_g & 0 & L_{gkq} \\ L_{akd} & 0 & 0 & L_{fkd} & 0 & L_{kd} & 0 \\ 0 & L_{akq} & 0 & 0 & L_{gkq} & 0 & L_{kq} \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \\ i_o \\ i_f \\ i_g \\ i_{kd} \\ i_{kq} \end{bmatrix}$$

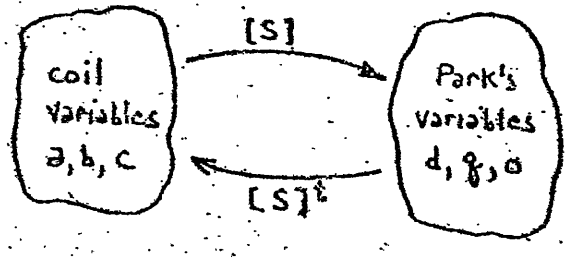
34e-1

$$[S] = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{4\pi}{3}) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

$$\vec{y}_{coil} = \begin{pmatrix} y_a \\ y_b \\ y_c \end{pmatrix} \qquad \vec{y}_{park} = \begin{pmatrix} y_d \\ y_q \\ y_o \end{pmatrix}$$

$$\vec{y}_{park} = [S]\,\vec{y}_{coil}$$

$$[S]^{-1} = [S]^t \quad \text{(orthogonal)}$$



$$HJ_k \frac{d^2\theta_k}{dt^2} + D_k \frac{d\theta_k}{dt} + DELOMP_k \cdot \left(\frac{d\theta_k}{dt} - 2\pi f\right)$$

$$+\ DMUT_{k,k+1} \cdot \left(\frac{d\theta_k}{dt} - \frac{d\theta_{k+1}}{dt}\right) + DMUT_{k-1,k} \cdot \left(\frac{d\theta_k}{dt} - \frac{d\theta_{k-1}}{dt}\right)$$

$$+\ HKCO_{k,k+1} \cdot (\theta_k - \theta_{k+1}) + HKCO_{k-1,k} \cdot (\theta_k - \theta_{k-1}) = T_k^{mech} - T_{em}$$

Data Format for Dynamic Synchronous Machine

The specification of a dynamic synchronous machine source component withi an EMTP data case requires a number of data cards. These shall now be describ in order of data input, in groups, according to the following classification:

Class 1 S.M. data cards

First come three cards which specify the component type code, the voltage magnitude and angle in the steady-state, and names for the network nodes to which the armature windings are to be connected. The first of these 3 cards is for phase "a", as per the following format:

ITYPE	BUS	VOLT	FREQ	ANGLE
I2	A6	E10.6	E10.6	E10.6

ITYPE —— Type code for the dynamic synchronous machine component. Punch ITYPE = 59 .

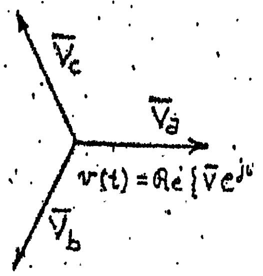
BUS —— Six-character EMTP network node name, punched in columns 3-8 as A6 information. The armature winding of phase "a" is to be connected to this node of the electric netwo

VOLT —— The steady-state voltage magnitude at the terminals of the machine. This is peak voltage (1.414 times RMS), line to neutral (.577 times line-to-line). Use units of volts .

FREQ —— The electrical frequency of the generator in Hz , for steady-state operation. For North American systems, this will be 60.

ANGLE —— The steady-state voltage phasor angle at the terminals of th machine, for phase "a" . Units are degrees. This machin component, all other ones, and all sinusoidal voltage or current sources of Type 14 are assumed to all have the same reference for phase angles, of course.

Conventional positive sequence is assumed, as this term is used in North America. That is, phase "b" voltage lags phase "a" voltage by 120 degrees (and "c" leads "a" by 120 degrees). See sketch.



The 2nd of 3 cards in Class 1 serves only to name the network connection for phase "b" of the machine. Punch the appropriate "b"-phase name in columns 3-8 using A6 format, and leave the rest of the card blank.

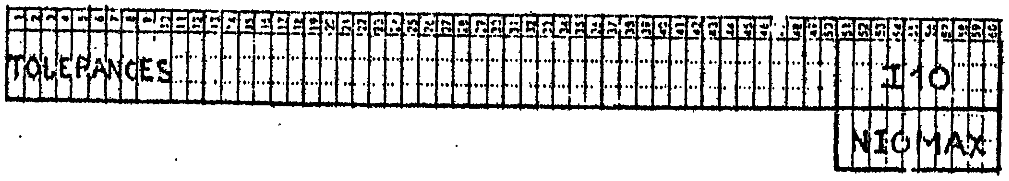
The 3rd of 3 cards in Class 1 serves only to name the network connection for phase "c" of the machine. Punch the appropriate "c"-phase name in columns 3-8 using A6 format, and leave the rest of the card blank

Class 2 S.M. data cards

Next in order of data input come optional special-request cards (if any) which are associated with the machine. There are two such possible cards, with format and meaning as desciibed immediately below. Ordering of such cards (if two or more) within the Class 2 grouping is arbitrary.

a) "TOLERANCES" special-request card

There is just one parameter related to the solution of the dynamic S.M. component which may be redefined by the user, if so desired. This is accomplished by means of an optional special-request card of the following format:

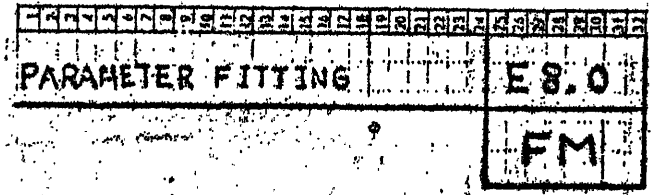


NIOMAX (51-60) ---- Given a default value of 10, "NIOMAX" indicates the number of terms which are to be used in a rational approximation to the state transition matrix. Note that this is not an iteration limit, but rather the actual number of terms which will be used. As a general rule, never use less than six. Ten (the default value) has proven adequate for all data cases run thus far, so the user should not have to fiddle with this parameter.

It should be stressed that the parameter on the "TOLERANCES" card is a scalar variable only; it applies to the entire data case, rather than just to the specific machine along with which the input occurred.

b) "PARAMETER FITTING" special-request card

Commonly-available S.M. test data turns out to actually be insufficient by itself to uniquely specify all parameters of the mathematical model (Park's equations) which is used by the EMTP. In the past, a simplified set of additional linear constraints has implicitely been added, thereby completing the parameter assignment. In the absence of a "PARAMETER FITTING" special-request card, this older, simpler procedure is used by the EMTP; machine parameters are not internally adjusted.



The PARAMETER FITTING card is also used to distinguish between different types of data. The presence of this card signals manufacturer's data.

Documentation of the mathematics used for "PARAMETER FITTING" is contained in Ref. 14; the procedure is explained in greater detail in Sections 2.3 and 2.4 of Reference 15, pages 12-18. For most EMTP users, however, such detailed machine considerations are too involved to be studied and understood in detail. Hence the only explanation presented here shall be a reproduction of the Abstract of Reference 14:

> The conversion of measurable machine parameters into resistances and self and mutual inductances needed for the computer model is presented. The commonly used, simplified set of equations is replaced by a set of more accurate, non-linear equations. While the differences between parameters found from the accurate and approximate relationships are not great for typical machine parameters, the method does avoid the uncertainty associated with approximations, which do not really have to be made any more. The method does not require any additional test data, but they may be easily incorporated, when available. The effects of saturation on the inductances are briefly discussed.

Perhaps a summary statement as to the effects of "PARAMETER FITTING" on the EMTP simulation results would be most valuable. Preliminary experiments would seem to indicate that armature currents and voltages, plus mechanical quantities on the shaft system, are only affected in a very minor way, typically. But rotor electrical quantities, and specifically the field current, may be significantly affected (ten to twenty per cent or more).

The "PARAMETER FITTING" process involves the iterative solution of a set of nonlinear equations by Newton's method. The initial (starting) guess is taken to be the values as produced by simplified historical approximation. If so requested by the user (in terms of the numerical parameter values which he actually inputs), the fitting process may be performed twice for each generator — once for the direct axis, and once for the quadrature axis. For a dual machine, this makes up to four such fittings per S.M. generator bus. If the original machine parameters are unrealistic, the iteration may not converge, and a warning message to this effect will be printed (see message number 47 of Section 2.2b). Nothing is lost in this case, however, since the EMTP will recover, and will simply use the input data without any optimized adjustment. Preliminary experimentation would seem to indicate that convergence will most probably occur for cases in which the following parameter relationships apply:

$$T'_{qo} > 10\,T''_{qo} \qquad T'_{do} > 10\,T''_{do} \qquad X''_{d} > 1.3\,X_{\ell} \qquad X''_{q} > 1.3\,X_{\ell}$$

It is here assumed that unsaturated parameter values are used, and the factors of 10 and 1.3 are sort of empirical estimates.

If resistances and reactances are used for the specification of machine parameters rather than standard manufacturer data, do not use the "PARAMETER FITTING" card. But if standard manufacturer data is being used, then there are several different cases of interest:

Case 0 : To disable the parameter optimization, punch value 2.0 for "FM".

Case 1 : If the user has a valid full set of S.M. data parameters (i.e., full transient and subtransient data which is not somehow degenerate), then usage of "PARAMETER FITTING" is optional; if used, "FM" should always be given a value of unity (FM = 1.0).

Case 2 : If the user has data in which $X_q' = X_q$ and $T_{qo}' \neq T_{qo}$, such parameters can be shown to be inconsistent. Without the usage of "PARAMETER FITTING" , the simulation can not even be run (an EMTP error stop will result). There are two options available to the EMTP user who punches data that satisfies such conditions:

a) If use is made of "PARAMETER FITTING" with parameter "FM" somewhere in the range $.95 < FM < 1.0$, then the EMTP will use all q-axis coils. Internally, however, the constraint $X_q' = FM \cdot X_q$ is observed (despite the user-punched equality of these two parameters).

b) If use is made of "PARAMETER FITTING" with parameter "FM" equal to unity ($FM = 1.0$), then the q-axis damper winding is dropped from the model; this leaves just one q-axis coil.

Case 3 : It is not uncommon for the user to have no data values for X_q' and T_q' In this case, he can still run the simulation if he does three things to the data:

1) Use "PARAMETER FITTING" with $FM = 1.0$;
2) Punch X_q' equal to the known X_q value;
3) Set (punch) $T_{qo}' = 0.0$.

In this case, the EMTP will drop the q-axis damper winding from the model, leaving just one q-axis coil.

Case 4 : Just like Case 2 , only with "q" (referring to the quadrature axis) replaced by "d" (referring to the direct axis).

Case 5 : Just like Case 3 , only with "q" replaced by "d" .

Case 6 : If the user wants to model a machine without any dampers at all on the q-axis, he should punch a common value for X_q , X_q' , and X_q'' . Any positive numbers can be used for T_{qo}' and T_{qo}'' . Even though not used in the calculation, such values will prevent misleading diagnostic messages.

Class 3 S.M. data cards

Next come either 3 or 4 cards, which specify the electrical parameters of the synchronous machine. The 1st of this group has the following format:

NUMAS	KMAC	KEXC	NP	SMOUTP	SMOUTQ	RMVA	RKV	AGLINE	S1	S2
I2	I2	I2	I4	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6

NUMAS —— The number of connected masses on the shaft system of this generator. A limit of 10 is presently imposed.

KMAC ——— The mass number which corresponds to the generator (or motor) rotor, within the interconnected mass-spring shaft system. Masses are to be numbered by the user for identification, beginning with number one on either end, and continuing sequentially (2, 3, ...) to the other end of the shaft. See Figs. 3 and 4 at the very beginning of Section 1.62 .

KEXC ——— The mass number which corresponds to the exciter on the shaft system. If no exciter exists, leave this field blank.

NP ——— The number of poles (not pole pairs) which charact rize the machine rotor. The electrical frequency of the machine is equal to the mechanical frequency times NP / 2 , recall.

SMOUTP —— Proportionality factor which is used only to split the real power among the two halves of a dual machine during the machine initialization. If a single machine, this field may be ignored. If a dual machine, suppose that the user punches value PA for this half of the dual, and value PB for the other half; then the fraction PA / (PA + PB) of the total steady-state real power output will be assigned to this half of the dual during machine initialization.

SMOUTQ —— The same as "SMOUTP" , only for reactive rather than real power.

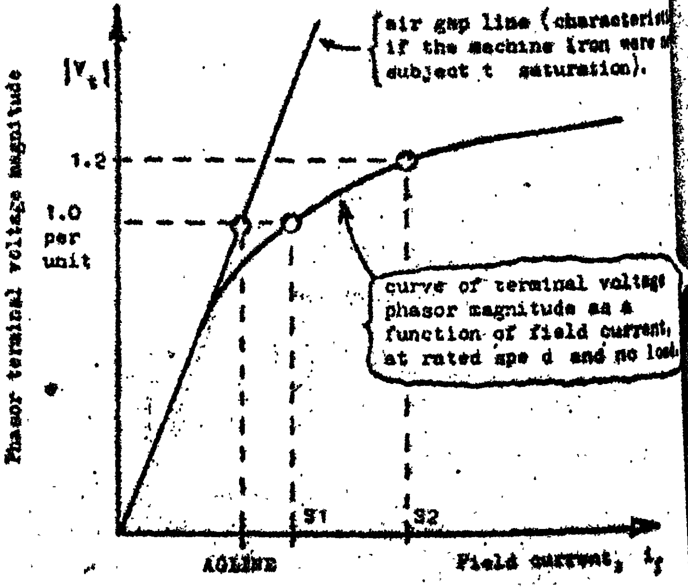
RMVA ——— The total 3-phase volt-ampere rating of the machine, in units of MVA (million volt-amperes).

RKV ——— The rated line-to-line voltage of the machine, in units of RMS kV . Taken as a pair, "RKV" and "RMVA" define the base values upon which per unit machine parameters are assumed to apply, it may be noted.

AGLINE —— Value of the field current in amperes which will produce rated armature voltage (1.0 per unit) on the air gap lin . This is an indirect specification of the mutual inductance between the field and the armature of the machine. See sketch below. If the S.M. is saturable, append an extra minus sign (making "AGLINE" negative) as a flag.

S1 ——— Value of the field current in amperes which will produce rated armature voltage (1.0 per unit) on the no-load saturation curve. See right. This field, as well as "S2" , can be left blank if the S.M. is not saturable.

S2 ——— Like "S1" , only for 120% of rated voltage (1.2 per unit).



The parameters "AGLINE" , "S1" , and "S2" just inputted actually apply to the d-axis of the machine. A second card can follow --- call it Card 1a (as an extension of Card 1) --- to provide for the same three parameters, only for the q-axis:

AGLQ	S1Q	S2Q
E10.6	E10.6	E10.6

If there is to be no saturation modeling for the q-axis, this card can be omitted or left blank. Nonzero values of "AGLQ" indicate saturation as follows:

AGLQ > 0 : Here the q-axis air-gap line is known, and AGLQ is the value of the field current in amperes which will produce rated armature voltage on that line. Data fields "S1Q" and "S2Q" must not be left blank (supply correct values).

AGLQ < 0 : The negative value for AGLQ is a flag indicating that the user does not know the air-gap line for the q-axis, but the user does want q-axis saturation modeling. The EMTP will proceed to internally generate an approximate value, and use it for q-axis saturation modeling. In this case, "S1Q" and "S2Q" can be left blank, and -1.0 can be used for "AGLQ" .

The remaining cards of Class 3 S.M. data depend upon whether standard manufacturer-supplied data are being used. If so (if "PARAMETER FITTING" card was used), two additional cards having the following format complete the Class 2 data:

R_a	X_ℓ	X_d	X_q	X'_d	X'_q	X''_d	X''_q
E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6

T'_{do}	T'_{qo}	T''_{do}	T''_{qo}	X_o	R_n	X_n
E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6

R_a ——— Armature resistance, in per unit. This must be non-negative.

X_ℓ ——— Armature leakage reactance, in per unit. If unknown, use the smallest of X''_d, X''_q, and X_o.

X_d ——— Direct-axis (d-axis) synchronous reactance, in per unit.

X_q ——— Quadrature-axis (q-axis) synchronous reactance, in per unit.

X'_d ——— Direct-axis (d-axis) transient reactance, in per unit.

X'_q ——— Quadrature-axis (q-axis) transient reactance, in per unit.

X''_d ——— Direct-axis (d-axis) subtransient reactance, in per unit.

X''_q ——— Quadrature-axis (q-axis) subtransient reactance, in per unit.

T'_{do} ——— Direct-axis (d-axis) open-circuit transient time constant, in seconds.

T'_{qo} ——— Quadrature-axis (q-axis) open-circuit transient time constant, in seconds.

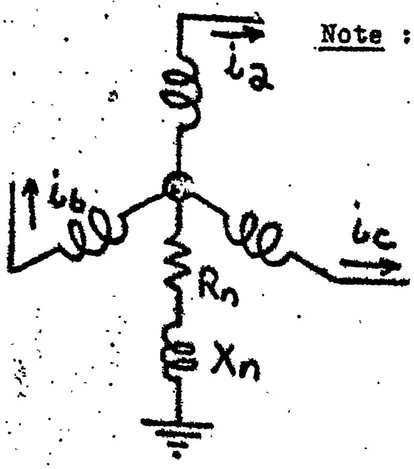
T''_{do} ——— Direct-axis (d-axis) open-circuit subtransient time constant, in seconds.

T''_{qo} ——— Quadrature-axis (q-axis) open-circuit subtransient time constant, in seconds.

X_o ——— Zero-sequence reactance, in per unit. If this is unknown, it is suggested that the same value as for X''_d or X_ℓ be used. See note below.

R_n ——— The real part of the neutral grounding impedance, in per unit. See note below.

X_n ——— The imaginary part of the neutral grounding impedance, in per unit.



Note : The machine is assumed to have a Wye-connected armature, with the neutral connected to ground through the impedance $R_n + jX_n$. If the machine is in fact ungrounded (but still Wye-connected), simply use a large grounding impedance. Vladimir recomme 100 per unit or more; either R or X (he has used both) This is done in Toronto, where Univac word length is only Vladimir reports no numerical trouble.

On th other hand, should the user have chosen to describe the machine by means of per unit inductance and resistance matrices (no "PARAMETER FITTING" card used), then the Class 2 S.M. data is completed with three cards of the following format:

L_f	L_{af}	L_{fkd}	L_d	L_{akd}	L_{kd}
E10.6	E10.6	E10.6	E10.6	E10.6	E10.6

L_g	L_{ag}	L_{gkq}	L_q	L_{akq}	L_{kq}
E10.6	E10.6	E10.6	E10.6	E10.6	E10.6

X_o	R_a	R_f	R_{kd}	R_g	R_{kq}	R_n	X_n
E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6

L_f —— The self-inductance of the field winding (circuit number 1 on the direct axis (d-axis) of the rotor), in per unit.

L_{af} —— The mutual-inductance coefficient between the armature and the field winding (circuit number 1 on the direct axis (d-axis) of the rotor), in per unit.

L_{fkd} —— The mutual-inductance coefficient between the field winding (circuit number 1 on the direct axis (d-axis) of the rotor) and the direct axis damper winding (circuit number 2 on the direct axis (d-axis) of the rotor), in per unit.

L_d —— The self-inductance coefficient for the direct axis (d-axis) of the armature, in per unit.

L_{akd} —— The mutual-inductance coefficient between the armature and the direct axis damper winding (circuit number 2 on the direct axis (d-axis) of the rotor), in per unit.

L_{kd} —— The self-inductance of the direct axis damper winding (circuit number 2 on the direct axis (d-axis) of the rotor), in per unit.

Not : Direct-axis parameters L_{af}, L_{fkd}, and L_{akd} are generally assumed to all be equal. But this is not a constraint of the EMTP cod . Unequal values can be used, if available.

Numbering of windings on the direct axis (d-axis) :
- #1 —— field winding of machine
- #2 —— d-axis damper winding

Numbering of windings on the quadrature axis (q-axis) :
- #1 —— q-axis damper winding
- #2 —— eddy current winding

L_g —— The self-inductance of the q-axis damper winding (circuit number 1 on the quadrature axis (q-axis) of the rotor), in per unit.

L_{ag} —— The mutual inductance coefficient between the armature and the q-axis damper winding (circuit number 1 on the quadrature axis (q-axis) of the rotor), in per unit.

L_{gkq} —— The mutual inductance coefficient between the two circuits on the quadrature axis (q-axis) of the rotor, in per unit.

L_q —— The self-inductance coefficient for the quadrature axis (q-axis) of the armature, in per unit.

L_{akq} —— The mutual-inductance coefficient between the armature and the eddy-current winding (circuit number 2 on the quadrature axis (q-axis) of the rotor), in per unit.

L_{kq} —— The self-inductance of the eddy-current winding (circuit number 2 on the quadrature axis (q-axis) of the rotor), in per unit.

Note : Quadrature-axis parameters L_{ag} , L_{gkq} and L_{akq} are generally assumed to all be equal. But this is not a constraint of the EMTP code. Unequal values can be used, if available.

X_o —— Zero-sequence reactance, in per unit. If this is unknown, it is suggested that the same value as for X''_d or X_ℓ be used. See note about Wye-connection 2 pages back.

R_a —— Armature resistance, in per unit.

R_f —— Resistance of the field winding (winding number 1 on the direct axis), in per unit.

R_{kd} —— Resistance of the damper winding on the direct-axis (d-axis) of the rotor, in per unit. This is the resistance of winding number 2 on the d-axis of the rotor.

R_g ——— Resistance of the q-axis damper winding (winding number 1 on the quadrature axis (q-axis) of the rotor), in per unit.

R_{kq} ——— Resistance of the eddy-current winding (winding number 2 on the quadrature axis (q-axis) of the rotor), in per unit.

R_n ——— The real part of the neutral grounding impedance, in per unit.

X_n ——— The imaginary part of the neutral grounding impedance, in per unit.

} See note about Wye-connected armature three pages back.

Class 4 S.M. Data cards

Next in order of data input come the mass cards which contain mechanical parameters for the shaft system. There is to be one such card for each mass, punched according to the format immediately below. In number, there are "NUMAS" such cards (see 1st card of Class 3 data, columns 1-2); ordering is actually immaterial (the mass cards can be shuffled), though it is generally clearer to stack such cards in naturally-increasing order of the mass number "ML".

ML		EXTRKS	HJ	DELDMP	DMUT	HKCO	D
I2		E10.6	E10.6	E10.6	E10.6	E10.6	E10 6

ML ——— The mass number, to be punched in the field of columns 1-2 using I2 format. Recall that masses are to be numbered by the user beginning with number one on either end of the shaft system, and continuing sequentially (2, 3, ...) to the other end. See Figs. 3 and 4 at the very beginning of Section 1.62.

EXTRKS ——— Punched in columns 11-20 (read using E10.6 format) is to be the fraction of the total external mechanical torque which is associated with this mass:

Generator : For a generator, enter the fraction of the total external mechanical torque of this shaft system which is applied to this particula mass. If a pump, enter a negative value.

Motor : For a motor, enter the fraction of the total external mechanical torque of the shaft system which is developed by this particular mass If a pump, enter a positive value.

HJ ——— The moment of inertia (WR^2) of mass number "ML" is read from the field of columns 21-30 using E10.6 format. This is to be in units of

$$\left[\text{million pound-feet}^2\right].$$

DELDMP ——— The speed-deviation self-damping coefficient for mass number "ML" is read from the field of columns 31-40 using E10.6 format. By definition,

$$T_i = \text{DELDMP}\ (\omega_i - \omega_s)$$

where T_i is this particular damping torque under consideration for mass number $i = ML$, ω_i is the angular velocity of mass i, and ω_s is the synchronous mechanical velocity for this shaft system. Data is to be punched in units of

$$\left[(\text{pound-feet}) / (\text{radians/second})\right]$$

DMUT ——— The mutual-damping coefficient is to be read from columns 41-50 using E10.6 format. This pertains to the present mass (assumed to be number $i = ML$) and the mass with the next higher number ($i+1$). The damping in question is a function of the velocity difference between the two masses:

$$T = \text{DMUT}\cdot(\omega_i - \omega_{i+1})$$

The mutual-damping coefficient is to be punched in units of

$$\left[(\text{pound-feet}) / (\text{radians/second})\right]$$

HKCO ——— The spring constant is to be read from columns 51-60 using E10.6 format. This pertains to the elastic connection between the present mass (assumed to b number $i = ML$) and the mass with the next higher number ($i+1$). Units for this data are

$$\left[(\text{million pound-feet}) / (\text{radian})\right]$$

D ——— The absolute-speed self-damping coefficient for this mass is to be read from columns 61-70 using E10.6 format. By definition,

$$T_i = D\cdot\omega_i$$

where T_i is the associated damping torque on mass number i, and ω_i is the angular velocity (absolute) of this mass. Units for this data are

$$\left[(\text{pound-feet}) / (\text{radians/second})\right]$$

It will be noted that fields "DMUT" and "HKCO" contain data which really does not belong exclusively to mass number $i = ML$; it also pertains equally to the mass which is numbered $i+1$. For mass card of the highest-numbered mass (number "NUMAS"), then, these two fields have no meaning, and are to be left blank.

Class 5 S.M. Data Cards

Next in order of data input comes a single output-variable specification card, which is to be punched according to the format described immediately below. Only those synchronous machine variables which are explicitely requested for output using this card will be a part of the EMTP output vector, which is used for both printing and plotting. The request scheme, unless otherwise noted below, is: "0" —— leave blank, or punch a zero, if no such output is desired;

"1" "2" —— punch unity or two for output in physical (MKS) units. No per unit output is possible

1	2	3	4	5	6	7	8	9	10	11	12	13 ...	13+LIMASS	13+2*LIMASS ....
JPAR	JMIC	JIDQO	JFI	JD2	JQ1	JQ2	JFV	JETM	JEIE	JIABC	JSAT	Angles θ_i $1 \leq i \leq$ LIMASS	Speeds ω_i $1 \leq i \leq$ LIMASS	Torques T_i $1 \leq i \leq$ LIMASS-1
I1	I1	I1	I1	I1	I1	I1	I1	I1	I1	I1	I1	all I1	all I1	all I1

JPAR 1 —— Controls printout of the machine inductances and resistances, plus the mechanical data of the shaft system, during the steady-state initial-condition printout.

Mneumonically, the "PAR" of the name "JPAR" comes from "parameter".

JMIC 2 —— Controls printout of the initial conditions for this synchronous machine, which are based on the EMTP steady-state phasor network solution. Mneumonically, the "MIC" of the name "JMIC" comes from "machine initial conditions. Punch 1 or 2 to get such output; leave blank (or punch a "0") to suppress it.

JIDQO 3 —— Controls printout of the armature currents in d-q-o coordinates (rotating reference frame), within the time-step loop. Mathematically, the notation used for these variables is i_d, i_q, and i_o; the EMTP names which are used for output identification are (all A6 format) "ID ", "IQ ", and "IO ". See also Col. 11.

JFI 4 —— Controls printout of the current in the field winding of the machine (circuit number 1 on the direct axis). Mathematical notation for this is i_f; the EMTP name which is used for output identification is "IF ".

JD2 5 —— Controls printout of the current in the damper winding of the direct axis (d-axis) of the machine. The winding in question is winding number 2 on the d-axis. Mathematical notation for the current is i_{kd}. the EMTP name which is used for output identification is "IKD ".

JQ1
6.

Controls printout of the current in the q-axis damper winding (circuit number 1 on the quadrature axis (q-axis) f the rotor). Mathematical notation for this current is i_g ; the EMTP name which is used for output identification is IG ".

JQ2
7

Controls printout of the current in the eddy-current winding (circuit number 2 on the quadrature axis (q-axis) of the rotor). Mathematical notation for this current is i_{kq} . the EM name which is used for output identification is "IKQ

JFV
8

Controls printout of the voltage which is applied to the field winding by the exciter. This will be a constant (dc) voltage, unless the user explicitely specifies a connection to TACS exciter dynamics as part of the Class. 6 S.M. data cards to follow. The field winding is winding number 1 on the direct axis (d-axis) of the machine. Mathematical notation for the variable in question is v_f ; the EMTP name which is used for output identification is "VF "

JETM
9

Controls printout of the net externally-applied torque on the machine rotor. This will equal the electromechanical torque of the machine, except in cases where there is also an external mechanical torque which is applied directly to the machine rotor (e.g., the case of a single-mass representation for the shaft system). More precisely, it is $T_m - T_e$ which is printed out . The EMTP name which is used for output identification is "TQ GEN" . The sign convention is such that this torque will normally be negative for a generator (in the steady state).

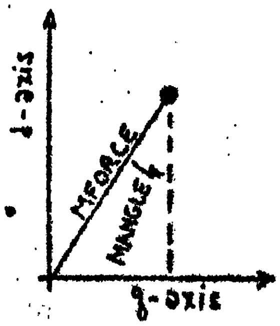
JETE
10

Control. printout of the net externally-applied torque on the exciter rotor. This will equal the electromechanica torque of the exciter, except in unusual ca es wher ther may be an external mechanical torque applied to th exciter rotor. The EMTP name which is used for output identification is "TQ EXC" . The sign convention is such that this torque will normally be negative for a generator operating in the steady state.

JIABC
11

Controls printout of the machine armature currents in phase coordinates (actual coil variables), within the time-step loop. Mathematically, the notation used for these variable is i_a , i_b , and i_c ; the EMTP names which are used for output identification are (all A6 format) "IA ", "IB ", and "IC ". See also variable "JIDQO" of column 5, which also provid for armature current output, only in d-q-o coordinates.

JSAT 12 ------- Control the printout of the machine flux; or more precisely, of the magnetomotive force (MMF) which drives it. If this output is selected, two EMTP variables are produced: one for the magnitude of the flux, and the other for the angle (see sketch at left). The EMTP names which are used for output identification of these variables are "MFORCE" and "MANGLE" , respectively. Units of the output are ampere-turns and radians , respectively.



θ_i ——— The I1 field of column 12 + i controls printout of the mechanical angle θ_i of mass number i , for i being a positive integer which does not exceed "LIMASS" .

For a definition of "LIMASS" , see one paragraph below.

Units of output are degrees . The angles in question are all measured with respect to a synchronously-rotating reference frame; they will be constant, then, for the case of a machine which is operating in the sinusoidal steady-state. For an unloaded machine which is operating in the steady state with no externally applied torques and no losses, all angles would equal +90 degrees. The EMTP name which is used for output identification of the angle θ_i of mass I is "ANG I " .

For example, the name associated with the angle of mass number nine is "ANG 9 " , while that for mass number thirteen is "ANG 13" .

"LIMASS" is the program limit on the number of masses, as determined by FORTRAN dimensioning of the EMTP. Unless altered locally by Program Maintenance (for instructions, see the end of Section 1.62b), this will be equal to 10 .

ω_i ——— The I1 field of column 12 + LIMASS + i controls printout of the angular velocity ω_i of mass number i , for i being a positive integer that does not exceed "LIMASS" . This output is simply the derivative of the corresponding θ_i which has been described in more detail immediately above. Units for this output are radians/second . The EMTP name which is used for output identification of the mechanical angular velocity ω_i of mass I is "VEL I " .

$T_{i,i+1}$ ——— The I1 field of column 12 + 2*LIMASS + i controls printout of the torque on the shaft which connects mass number i with mass number i+1 , for i a positive integer that does not exceed one less than "LIMASS" The EMTP name which is used for output identification of the shaft torque in question (between mass i and mass i+1) is "TOR I " . Units of the output are million newton-meters .

For EMTP output and plotting purposes, the just-delineated output variables are actually identified by a pair of 6-character names. The second name (lower name of printed pair) identifies the variable type mneumonically, as documented above. The first name (upper name of printed pair) identifies the generator in question, in order of data input. For example, "MACH 3" would be for the third machine (assumed here to be a single), while "MAC 2B" would be for part "B" of the second machine (here assumed to be a dual, for purposes of illustration). A specific example of such column headings of printed EMTP time-step-loop output follows:

```
COLUMN HEADINGS FOR THE  28  EMTP OUTPUT VARIABLES FOLLOW.   THESE ARE ORDERED ACCORDING TO THE FIVE
POSSIBLE EMTP OUTPUT-VARIABLE CLASSES, AS FOLLOWS ....
   FIRST  12  OUTPUT VARIABLES ARE ELECTRIC-NETWORK NODE VOLTAGES (WITH RESPECT TO LOCAL GROUND);
    NEXT   0  OUTPUT VARIABLES ARE BRANCH VOLTAGES (VOLTAGE OF UPPER NODE MINUS VOLTAGE OF LOWER NODE);
    NEXT   3  OUTPUT VARIABLES ARE BRANCH CURRENTS (FLOWING FROM THE UPPER EMTP NODE TO THE LOWER);
    NEXT  13  OUTPUT VARIABLES PERTAIN TO DYNAMIC SYNCHRONOUS MACHINES, WITH NAMES GENERATED INTERNALLY;
   FINAL   0  OUTPUT VARIABLES BELONG TO  'TACS'  (NOTE INTERNALLY-ADDED UPPER NAME OF PAIR).
BRANCH POWER  CONSUMPTION (POWER  FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH VOLTAGE FOR THIS GROUPING;
BRANCH ENERGY CONSUMPTION (ENERGY FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH CURRENT FOR THIS GROUPING.
 STEP    TIME        C2          B2          A2          A3          C3          B3          A1          B1

                     A4          B4          C4          A1          B1          C1          MACH 1      MACH 1
                                                         A2          B2          C2          IO          IO
                     MACH 1      MACH 1      MACH 1      MACH 1      MACH 1      MACH 1      MACH 1      MACH 1
                     IF          IKD         IG          IKQ         TQ GEN      IA          IB          IC
                     MACH 1
                     VEL 1
```

Alternate expanded format for Class 5 S.M. data

An alternate format to that which has just been presented for Class 5 S.M. data is available. It is less compact (usually requiring two cards rather than just one), but is more flexible in some ways, as shall now be explained.

First there is to appear one card which bears a 6-character key word, plus the first twelve variables of the original compact format:

TEXT		JPAR	JMIC	JICQD	JFT	JD2	JQ1	JQ2	JFY	JETM	JETE	JIABC	JSAT
A6		I5	I5	I5	I5	I5	I5	I5	I5	I5	I5	I5	I5

TEXT 1-6 ——— 6-character key word, for which there are the following three options:

"ALL   " —— if all possible shaft variables (angles, velocities, and inter-mass torques) are to be outputted.

"NONE " —— if no possible shaft variables are to be outputted.

"EXTEND" —— if selective output of shaft variable is desired, as specified on an extension (continuation) card to foll

All other variables on the card (beginning with "JPAR" of columns 11-15) have exactly the same meaning as previously; they shall not be defined again here.

If "TEXT" (see above) were punched equal to "NONE " or "ALL ", then the just-described card would constitute all of the Class 5 S.M. data But should "EXTEND" be punched instead, then a second data card must follow, to define the desired shaft output quantities:

..... LIMASS	....2*LIMASS	.... 3*LIMASS-1
Angles θ_i $1 \leq i \leq$ LIMASS	Speeds ω_i $1 \leq i \leq$ LIMASS	Shaft torques T_i $1 \leq i \leq$ LIMASS-1
all I1 format	all I1 format	all I1 format

The meaning of all quantities as used here is exactly the same as before

Class 6 S.M. Data Cards

Next in order of data input come cards which describe any interface connections between the machine under consideration, and TACS. The general format for the one or more such cards of Class 6 is as follows:

KK	BUS
I2	A6

Rule 1 : If the field voltage of the machine is to be controlled by exciter dynamics which have been modeled using TACS, then the following is required:

KK —— Punch "71" in columns 1-2, as a special request for the exciter connection.

BUS —— The 6-character name of a TACS variable is to be punched in columns 3-8. The numerical value of this TACS variable will then be used by the EMTP logic for the field voltage v_f of this machine.

If no such card is used, the EMTP logic will simply hold the field voltage for this machine constant, at whatever value was dictated by the initial conditions.

Rule 2 : If the total externally-applied power on the shaft system is to be controlled by dynamics which are modeled using TACS, then the following card is required:

KK —— Punch "72" in columns 1-2, as a special request for the TACS control of mechanical power.

BUS ---- The 6-character name of a TACS variable is to be punched in columns 3-8. The numerical value of this TACS variable will then be used by the EMTP logic as a multiplicative factor for scaling the otherwise-constant (steady-state) power values.

Should the user want to code the logic of this TACS connection, but temporarily bypass any associated dynamics, he can use the name "UNITY". Recall that this is the name of the built-in TACS source which has output identically equal to 1.0.

If no such card is used, the EMTP logic will simply hold the external mechanical powers on the rotor masses constant (at whatever values were dictated by the initial condition calculatio

Rule 2a : If the field voltage $v_f(t)$ and/or the field current $i_f(t)$ is to be passed into TACS from the machine, then the following is required. There can be either zero, or one, or two such cards:

KK ---- Punch "73" in columns 1-2 for field voltage v_f.

Punch "74" in columns 1-2 for field current i_f.

BUS ---- The 6-character name of the TACS source whose value is to be equal to the field voltage or current at each time step.

Rule 3 : If one or more mechanical angles θ_i, angular velocities ω_i, or shaft torques T_i of the shaft system of the machine are to be passed into TACS, then one data card must be punched for each such variable. Angles are in units of absolute radians (e.g., increasing by $2\pi f$ every second for 60Hz steady-state operation), angular velocities are in radians/second, and shaft torques are in million newton-meters. The data card format is:

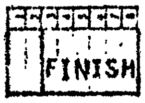
KK ---- The EMTP reads from columns 1-2 a code number which identifies the mechanical variable in question:

$$\begin{cases} \text{for } \theta_i, & \text{punch } i \\ \text{for } \omega_i, & \text{punch LIMASS} + i \\ \text{for } T_i, & \text{punch } 2\text{*LIMASS} + i \end{cases}$$

BUS ---- The EMTP reads from columns 3-8 a 6-character alphanumeric name. This field is to be punched with the name of the TACS source whose value is to be controlled by the machine variable in question.

Rule 4 : Ordering of the different possible cards which have just been described is immaterial; they can be shuffled, without altering the result.

Rule 5 : The end of all such cards as have just been described is to be indicated by a special terminator card Field "KK" is to be left blank, and field "BUS" is to be punched with the special word "FINISH" . Should this machine have no connections at all to TACS, then this "FINISH" record alone makes up the Class 6 S.M. data.



Class 7 S.M. Data cards

If the machine in question is not paralleled by one or more additional dynamic S.M. source components, then there is no Class 7 S.M. data. In this case, the "FINISH" card of the Class 6 data represents the final data card for this dynamic synchronous machine.

But suppose that a second dynamic S.M. is to be connected in parallel (armature windings connected to the same busses) with the one just inputted. Then the just-inputted "FINISH" card of Rule 5 must be modified to read "FINISH PART" , indicating to the EMTP that S.M. data for this 3-phase generator bus (to which armatures are connected) has only been partially completed. Class 7 data then consists of S.M. data cards for the second machine, beginning with Class 2 and ending with Class 6 .

This procedure can be generalized to apply to as many machines as the user wants to parallel on the same generator bus. For M machines, the first M-1 has data cards which end with a Rule-5 data card reading "FINISH PART" ; the final one ends with just "FINISH" , indicating to the EMTP that no other machines follow on that generator bus. Only the first of the M machines has any Class 1 data cards (since this applies to the common generator bus); all M-1 following machines skip this data.

1.62b TYPE-50 DYNAMIC SYNCHRONOUS MACHINE SOURCE COMPONENT

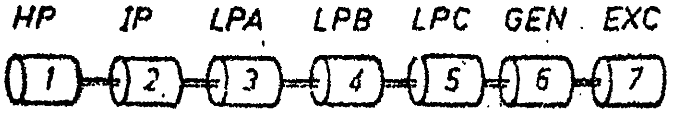


Fig. 3 Model of turbine-generator unit

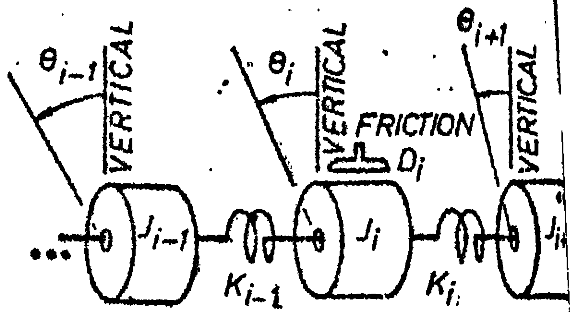
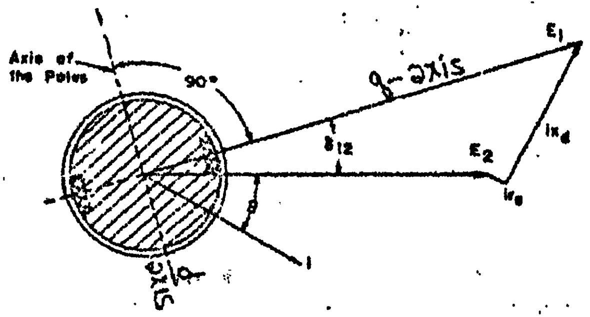


Fig. 4 Turbine-generat r part around mass i



General Description of Component

The dynamic synchronous machine component, an EMTP source by general classification, was developed at the Southern California Edison Co., as fully documented in Reference 8, Vol. VI, December 5, 1976. The dynamics of Park's (Blondel's) equations are provided for, with two rotor circuits on each axis. The mechanical side of the machine is modeled as an interconnection of masses and springs, plus viscous damping, thereby providing SSR (subsynchronous resonance) modeling capability. Either a single machine, or a dual machine (two machines in parallel, on the same generator bus), can be selected. Arbitrary control system dynamics, such as for representation of excitation systems, can be modeled by means of TACS (see Section 8.).

Initialization of the dynamic synchronous machine (values of state variables at time zero) is based on the EMTP phasor (sinusoidal steady-state) network solution. For this purpose, the user specifies a voltage magnitude and angle for the terminal bus of phase "a" ; it is internally extended to phases "b" and "c" by the EMTP, using the assumption of balanced, positive-sequence operation. Upon completion of the phasor network solution, the injected currents are known. Positive and negative sequence components are then used for the machine initialization. For unbalanced networks, note that this involves an approximation. See discussion to Ref. 16 by Drs. Dommel and Brandwajn.

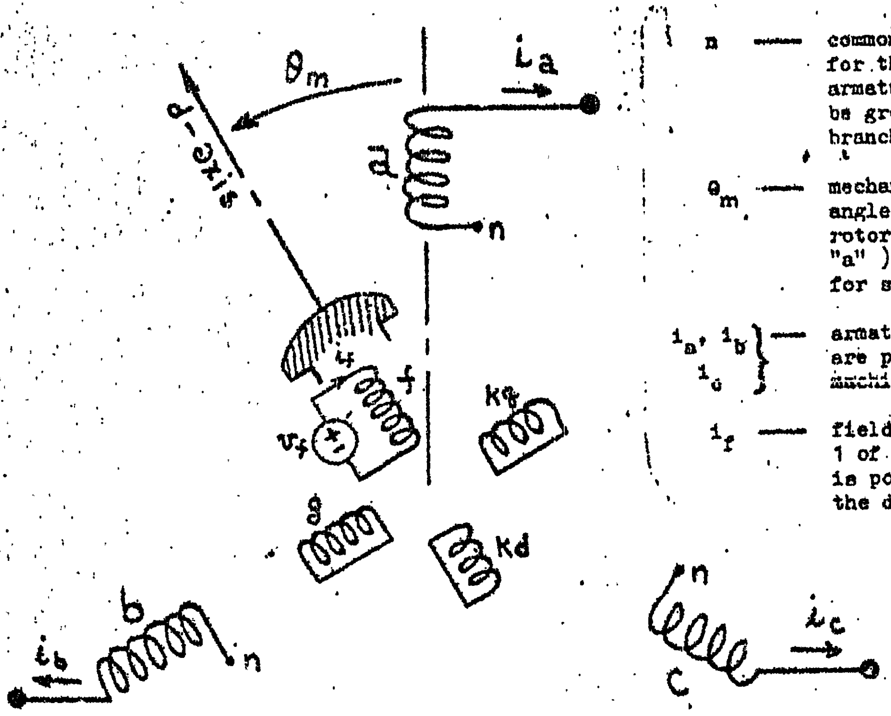
Should the user employ TACS for the representation of exciter dynamics, he must define the associated TACS initial conditions himself, manually. At this time, automatic initialization by the EMTP, based on the result of the machine initialization and the electric network solution, has not yet been worked out.

The dynamic synchronous machine component is internally balanced (with respect to the armature phases), and is inherently three-phase. The windings are assumed to be Wye-connected, with a possible R-L branch connecting the neutral to local ground. An alternate delta connection is available, by special request.

For output purposes, most machine parameters of interest are available — velocities and angles of the rotor masses, inter-mass shaft torques, and winding currents, for example. These are automatically appended to the regular EMTP output vector at the request of the user, so such variables are available for plotting as well as for printing.

Each rotor mass is allowed to have a constant mechanical torque applied to it (in addition to mechanical damping torques). The user specifies proportionality factors for each mass, with the actual constant torques then determined internally by the EMTP at the time of the sinusoidal steady-state initialization. This is the basic scheme, in the absence of special connections. But the user may represent governor dynamics if he so chooses, by using TACS to control the just-described torques. In this case, the required TACS output variable is a normalized multiplicative constant (equal to unity if it is to produce no effect) for scaling the otherwise-constant mechanical torques. A constant-power representation for the prime mover is one simple application which this torque connection to TACS allows for, it may be noted.

Even without any detailed explanation of where they come from, it might be desirable to document the set of equations which is used to model the S.M. We have:



n —— common neutral connection point for the three Wye-connected armature windings. This point may be grounded through a series R-L branch.

θ_m —— mechanical angle of the rotor (the angle between the direct axis of the rotor and the axis of armature phase "a"). Sketch is for a 2-pole machine, for simplicity.

i_a, i_b, i_c —— armature currents. Note that these are positive when flowing out of the machine (generator convention).

i_f —— field current (current in winding number 1 of the direct axis of the rotor). This is positive into the coil, in accord with the direction of steady-state flow.

f, kd —— rotor windings number 1 and 2 of the direct axis (d-axis), respectively.

g, kq —— rotor windings number 1 and 2 of the quadrature axis (q-axis), respectively.

Counter-clockwise steady-state rotation:

$$\frac{d\theta_m}{dt} = -\left(\frac{2}{NP}\right) \cdot 2\pi \, \text{FREQ}$$

Notes about mechanical equation (see lower right-hand corner of next page)

1) Coefficient names are as defined in the section about Class 4 S.M. data cards.
2) This equation is Newton's law in rotational form for mass number "k" , assuming the most general case.
3) If mass number "k" is not the generator rotor, omit the electromechanical torque T_{em} .
4) If mass number "k" is at one end of the shaft system, either mass number k-1 or mass number k+1 (or both, in the case of a single mass system) will not exist. In this case, the associated terms of mutual coupling ("DMUT" and "HKCO") are defined to be zero.
5) The synchronous mechanical frequency "f" enters only through the speed-deviation self-damping term.
6) As used here, θ_k is the absolute angle of mass number "k" of the shaft system.
7) T_k^{mech} is the externally-applied mechanical torque on mass number "k" , in the direction of $+\theta$.

$$v_d = -R_a i_d + \frac{d\lambda_d}{dt} - \lambda_q \frac{d\theta}{dt}$$

$$v_q = -R_a i_q + \frac{d\lambda_q}{dt} + \lambda_d \frac{d\theta}{dt}$$

$$v_o = -(R_a + 3R_n)\, i_o + \frac{d\lambda_o}{dt}$$

$$v_f = R_f i_f + \frac{d\lambda_f}{dt}$$

$$0 = R_g i_g + \frac{d\lambda_g}{dt}$$

$$0 = R_{kd} i_{kd} + \frac{d\lambda_{kd}}{dt}$$

$$0 = R_{kq} i_{kq} + \frac{d\lambda_{kq}}{dt}$$

$$T_{em} = \frac{NP}{6}\left(\lambda_d i_q - \lambda_q i_d\right)$$

$$\begin{bmatrix} \lambda_d \\ \lambda_q \\ \lambda_o \\ \lambda_f \\ \lambda_g \\ \lambda_{kd} \\ \lambda_{kq} \end{bmatrix} = \begin{bmatrix} -L_d & 0 & 0 & L_{af} & 0 & L_{akd} & 0 \\ 0 & -L_q & 0 & 0 & L_{ag} & 0 & L_{akq} \\ 0 & 0 & L_o & 0 & 0 & 0 & 0 \\ -L_{af} & 0 & 0 & L_f & 0 & L_{fkd} & 0 \\ 0 & -L_{ag} & 0 & 0 & L_g & 0 & L_{gkq} \\ -L_{akd} & 0 & 0 & L_{fkd} & 0 & L_{kd} & 0 \\ 0 & -L_{akq} & 0 & 0 & L_{gkq} & 0 & L_{kq} \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \\ i_o \\ i_f \\ i_g \\ i_{kd} \\ i_{kq} \end{bmatrix}$$

$$[S] = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

$$\vec{y}_{coil} = \begin{pmatrix} y_a \\ y_b \\ y_c \end{pmatrix} \qquad \vec{y}_{park} = \begin{pmatrix} y_d \\ y_q \\ y_o \end{pmatrix}$$

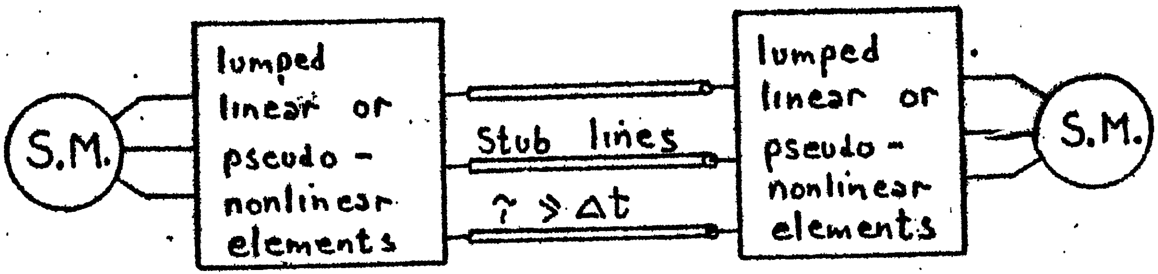
$$\vec{y}_{park} = [S]\, \vec{y}_{coil}$$

$$[S]^{-1} = [S]^t \quad \text{(orthogonal)}$$

$$\begin{tikzcd} \text{coil variables } a,b,c \arrow[r, bend left, "{[S]}"] & \text{Park's variables } d,q,o \arrow[l, bend left, "{[S]^t}"] \end{tikzcd}$$

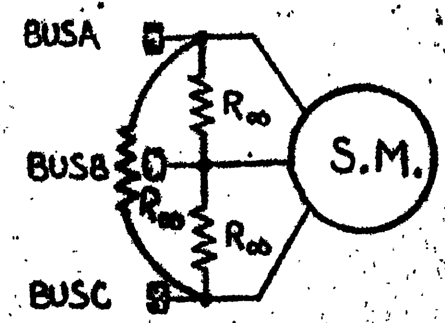
$$HJ_k \frac{d^2\theta_k}{dt^2} + D_k \frac{d\theta_k}{dt} + DELOMP_k \cdot \left(\frac{d\theta_k}{dt} - 2\pi f\right)$$
$$+ DMUT_{k,k+1} \cdot \left(\frac{d\theta_k}{dt} - \frac{d\theta_{k+1}}{dt}\right) + DMUT_{k-1,k} \cdot \left(\frac{d\theta_k}{dt} - \frac{d\theta_{k-1}}{dt}\right)$$
$$+ HKCO_{k,k+1} \cdot (\theta_k - \theta_{k+1}) + HKCO_{k-1,k} \cdot (\theta_k - \theta_{k-1}) = T_k^{mech} - T_{em}$$

Several points might be made, with regard to usage of this SCE dynamic S.M. EMTP source component. Most importantly, there is the underlying usage of 3-phase compensation* which requires that the dynamic S.M. busses be disconnected from each other by distributed parameter transmission lines. Such S.M. busses must also be so disconnected from any Type 91-93 true nonlinear or time-varying elements (see Section 1.3).


S.M.
lumped linear or pseudo - nonlinear elements
Stub lines
$\tau > \Delta t$
lumped linear or pseudo - nonlinear elements
S.M.

If no such lines exist naturally, then the user must make them up himself. Thre uncoupled single-phase stub lines, having travel time equal to or slightly in excess of "DELTAT" , can conveniently be used. In crude general terms, this would require something like 20 miles of overhead line, in the case of a time-step size of 100 microsec (since light travels about one mile in five microseconds). Note that such an impedance would not really be negligible, so one does not want to simply add it to the actual problem modeling. Rather, one subtracts the associated inductance from some lumped element (e.g., from transformer leakage reactance); and then merely "distributes it" in this way. A line of Section 1.26 is usually used for the stub, with zero resistance (making it distortionless). Mike Hall of SCE has reported good success with this technique.

The user should also be aware that the EMTP will add high-impedance branches across the armature terminals of any dynamic S.M. which is not "symmetrically connected" to a distributed line or a Pi-circuit or coupled R-L (3-phase) branch. This is to insure inter-phase coupling, as needed for the compensation usage (don't ask me why now; I forget! But John and Mike of SCE found out experimentally that such coupling *was* necessary). The user will be notified of the internal addition of such resistors by means of Message 3 of Section 2.2b . See further discussion there. The value of the added resistors can be controlled by the user, if need be (see the "HIGH RESISTANCE" request of Section 1.0c).



Users of the dual-machine capability (type codes 51 or 53 on following page) must also observe the following additional restriction: any and all dual machines must precede any single machines, in the order of data input.

---

*Note: The term "compensation" as used here has nothing to do with capacitors or reactors (as the term is used in system planning circles). Rather, it refers to the mathematics of superposition as used in linear network theory. Single-phase compensation of the EMTP is fully described in Reference 2; Section 1.3-A-b of this User's Manual discusses the consequences to the EMTP user

Data Format for Dynamic Synchronous Machin

The specification of a dynamic synchronous machine source component within an EMTP data case requires a number of data cards. These shall now be described in order of data input, in groups, according to the following classification:

Class 1 S.M. data cards

First come three cards which specify the component type code, the voltage magnitude and angle in the steady-state, and names for the network nodes to which the armature windings are to be connected. The first of these 3 cards is for phase "a" , as per the following format:

ITYPE	BUS	VOLT	FREQ	ANGLE
I2	A6	E10.6	E10.6	E10.6

ITYPE —— Type code for the dynamic synchronous machine component. Four are available at the present time:

- 50 —— single machine, characterized by standard manufacturer-provided electrical data which will be specified in per unit.
- 51 —— Like 50 , only for a dual machine.
- 52 —— single machine, characterized by per unit inductance and resistance matrices.
- 53 —— Like 52 , only for a dual machine.

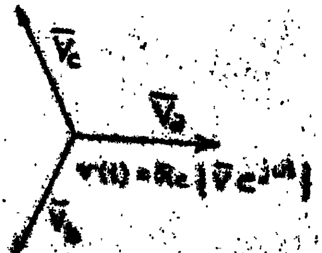
BUS —— Six-character EMTP network node name, punched in columns 3-8 as A6 information. The armature winding of phas "a". is to be connected to this node of the electric network

VOLT —— The steady-state voltage magnitude at the terminals of the machine. This is peak voltage (1.414 times RMS), line to neutral (.577 times line-to-line). Use units of volts .

FREQ —— The electrical frequency of the generator in Hz , for steady-state operation. For North American systems, this will be 60.

ANGLE —— The steady-state voltage phasor angle at the terminals of the machine, for phase "a" . Units are degrees. This machine component, all other ones, and all sinusoidal voltag or current sources of Type 14 are assumed to all have the same reference for phase angles, of course.

Conventional positive sequence is assumed, as this term is used in North America. That is, phase "b" voltage lags phase "a" voltage by 120 degrees (and "c" leads "a" by 120 degrees). See sketch.



The 2nd of 3 cards in Class 1 serves only to name the network connection for phase "b" of the machine Punch the appropriate "b"-phase name in columns 3-8 using A6 format, and leave the rest of the card blank

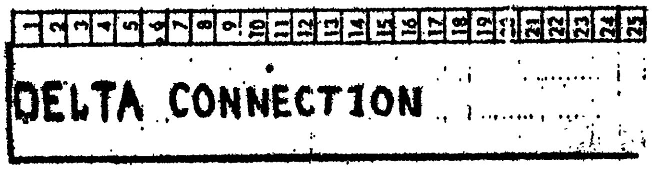
The 3rd of 3 cards in Class 1 serves only to name the network connection for phase "b" of the machine. Punch the appropriate "c"-phase name in columns 3-8 using A6 format, and leave the rest of the card blank.

Class 2 S.M. data cards

Next in order of data input come optional special-request cards (if any) which are associated with the machine. There are three such possible cards, with format and meaning as described immediately below. Ordering of such cards (if two or more) within the Class 2 grouping is arbitrary.

a) "DELTA CONNECTION" special request card

If the armature windings of the dynamic S.M. are delta-connected (rather than Wye-connected), then this status must be communicated to the EMTP by a special-request card which bears the text "DELTA CONNECTION" in columns 1-16:



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
D	E	L	T	A		C	O	N	N	E	C	T	I	O	N									

In the absence of such a card, the machine is assumed to be Wye-connected (which is by far the most common situation, for large power system generators). Except for the possible presence of this one special-request card, no other portion of the S.M. data specification explicitely makes reference to how the armature windings are connected.

For a machine the armature windings of which are delta-connected, a word about the interpretation of EMTP S.M. armature-current printout is in order. The labeling of variables is not altered (from that used for a Wye connection), so the user must be very careful. There are four situations, depending upon whether one considers initial conditions or time-step-loop printout, and whether coil variables or Park's variables. Of these four, one will be incorrectly labeled.

a) For the time-step loop output, there is no confusion or labeling problem. The user must simply remember that "IA", "IB", and "IC" are line currents (not armature winding currents), while "ID", "IQ", and "I0" are indeed armature winding variables (albeit in Park's coordinates).

b) For the steady-state initial-condition printout, "ID", "IQ", and "I0" are indeed armature-winding variables, just as in Point a). But "IA", "IB", and "IC" are erroneously labeled (see sketch), for they are armature coil variables. E.g., what is labeled "IA" in the S.M. initial condition printout is actually i_{ab}, the current from "a" to "b" in the winding

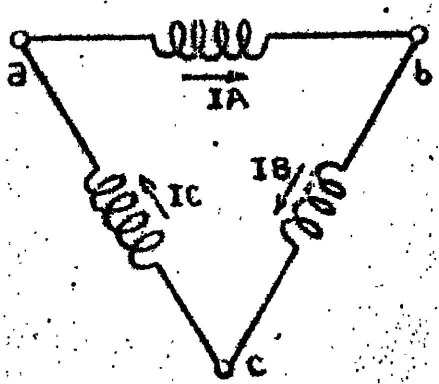


Fig. A. Erroneous initial-condition labeling, delta connection.

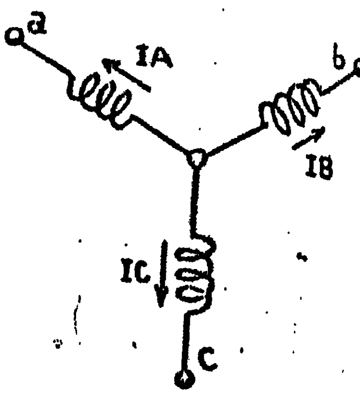


Fig. B. Conventional Wye labeling.

Restriction : The option of "DELTA CONNECTION" is not allowed for a dual machine. If such a rare configuration should ever arise, the user is required to isolate the machines by distributed-parameter transmission lines (just as with a Wye-connection and three or more in parallel). See Section 1.3 for further comments.

b) "TOLERANCES" special-request card

A number of control parameters related to the solution of the dynamic S.M. component may be re-defined by the user, if so desired. This is accomplished by means of an optional special-request card of the following format:

TOLERANCES	E10.0	E10.0	E10.0	I10	I10
	EPSUBA	EPOMEG	EPDGEL	NIAMAX	NIOMAX

EPSUBA —— Tolerance associated with the calculation of the state transition matrix of the S.M. equation set. The power-series accumulation is terminated (assumed to have converged) when terms become smaller than this residual tolerance. See "NIAMAX" below for a limit on the number of power series terms.

EPOMEG —— Tolerance associated with the iterative calculation of S.M. rotor speed at each time step of the simulation. The calculation is assumed to have converged when the speed correction in per unit is less than this tolerance.

EPDGEL —— Tolerance associated with singularity of the coefficient matrix of the linear S.M. equations which must be solved at each time step. In general terms, the meaning and usage is comparable to the EMTP usage of floating-point miscellaneous data parameter "EPSILN" for the electric network solution.

NIAMAX —— Maximum number of power series terms which are allowed, for the evaluation of the state transition matrix of the S.M. equation set. If tolerance "EPSUBA" (see above) is not achieved within "NIAMAX" terms, the data case is terminated with an EMTP error message to that effect.

NIOMAX —— Maximum number of iterations which are allowed for the calculation of the S.M. rotor speed, at any time step. If tolerance "EPOMEG" is not achieved within "NIOMAX" iterations, then the data case is terminated with an EMTP error message to that effect.

It should be stressed that these are scalar variables only; they apply to the entire data case, rather than just to the specific machine along with which they were defined. For example, the user may have 3 EMTP dynamic S.M. source components in his data case under consideration. But there is only one "EPOMEG", and the rotor speeds of all 3 machines will be iterated until convergence is achieved to this same single tolerance. Should the user desire to re-define "EPOMEG", the "TOLERANCES" special-request card which performs this function could accompany the data cards for any one (or all three, if one wants to be redundant) of the 3 machines.

Only non-blank (non-zero) fields of the "TOLERANCES" card serve to re-define the associated variables. Hence the user need only punch those fields which are associated with control parameters which he actually wants to re-define.

In the absence of re-definition by means of a "TOLERANCES" special-request card, values for the associated variables remain at the default values which are assigned within installation-dependent module "SYSDEP" of overlay number 1. See Program Maintenance, if there is a question about these values. As set up for REAL*8 IBM computation and 60-bit CDC computation in the Spring of 1977, the following are default values for tolerances:

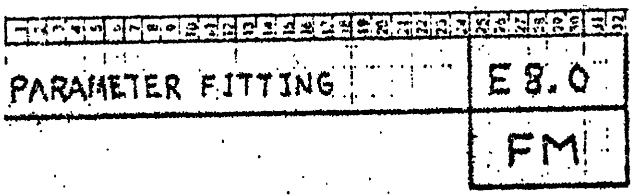
EPSUBA = 1.E-16 EPOMEG = 1.E-15 , EPDGEL = 1.E-16
NIOMAX = 10 NIAMAX = 50

For machines with reduced precision (e.g., single-precision Honeywell, Univac, or DEC PDP-10, all of which use 36-bit floating-point computation), the three floating-point parameters must be reduced. This should properly be done within installation-dependent module "SYSDEP" of overlay 1. The following values are used by Ontario Hydro for their 36-bit Univac EMTP version: EPSUBA = 1.E-8 , EPOMEG = 1.E-8 , and EPDGEL = 1.E-8 . Integer parameters are unaffected.

c) "PARAMETER FITTING" special-request card

Commonly-available S.M. test data turns out to actually be insufficient by itself to uniquely specify all parameters of the mathematical model (Park's equations) which is used by the EMTP. In the past, a simplified set of additional linear constraints has implicitely been added, thereby completing the parameter assignment. In the absence of a "PARAMETER FITTING" special-request card, this older, simpler procedure is used by the EMTP; machine parameters are not internally adjusted.

But, should the user desire an "optimized" adjustment of the S.M. parameters, then he is to supply a special-request card of the following format:



Note that there is only one variable ("FM") associated with such a data card; its usage is explained further below.

Documentation of the mathematics used for "PARAMETER FITTING" is contained in Ref. 14; the procedure is explained in greater detail in Sections 2.3 and 2.4 of Reference 15, pages 12-18. For most EMTP users, however, such detailed machine considerations are too involved to be studied and understood in detail. Hence the only explanation presented here shall be a reproduction of the Abstract of Reference 14:

> The conversion of measurable machine parameters into resistance and self and mutual inductances needed for the computer model is presented. The commonly used, simplified set of equations is replaced by a set of more accurate, non-linear equations. While the differences between parameters found from the accurate and approximate relationships are not great for typical machine parameters, the method does avoid the uncertainty associated with approximations, which do not really have to be made any more. The method does not require any additional test data, but they may be easily incorporated, when available. The effects of saturation on the inductances are briefly discussed.

Perhaps a summary statement as to the effects of "PARAMETER FITTING" on the EMTP simulation results would be most valuable. Preliminary experiments would seem to indicate that armature currents and voltages, plus mechanical quantities on the shaft system, are only affected in a very minor way, typically. But rotor electrical quantities, and specifically the field current, may be significantly affected (ten to twenty per cent or more).

The "PARAMETER FITTING" process involves the iterative solution of a set of nonlinear equations by Newton's method. The initial (starting) guess is taken to be the values as produced by simplified historical approximation. If so requested by the user (in terms of the numerical parameter values which he actually inputs), the fitting process may be performed twice for each generator —— once for the direct axis, and once for the quadrature axis. For a dual machine, this makes up to four such fittings per S.M. generator bus. If the original machine parameters are unrealistic, the iteration may not converge, and a warning message to this effect will be printed (see message number 47 of Section 2.2b). Nothing is lost in this case, however, since the EMTP will recover, and will simply use the input data without any optimized adjustment. Preliminary experimentation would seem to indicate that convergence will most probably occur for cases in which the following parameter relationships apply:

$$T'_{qo} > 10\ T''_{qo} \qquad T'_{do} > 10\ T''_{do} \qquad X''_d > 1.3\ X_\ell \qquad X''_q > 1.3\ X_\ell$$

It is here assumed that unsaturated parameter values are used, and the factors of 10 and 1.3 are sort of empirical estimates.

As for the choice of parameter "FM" and situations where "PARAMETER FITTING" might be useful, there are five distinct cases of interest:

Case 1 : If the user has a valid full set of S.M. data parameters (i.e., full transient and subtransient data which is not somehow degenerate), then usage of "PARAMETER FITTING" is optional; if used, "FM" should always be given a value of unity (FM = 1.0).

Case 2 : If the user has data in which $X'_q = X_q$ and $T'_{qo} \neq T_{qo}$, such parameters can be shown to be inconsistent. Without the usage of "PARAMETER FITTING" , the simulation can not even be run (an EMTP error stop will result). There are two options available to the EMTP user who punches data that satisfies such conditions:

a) If use is made of "PARAMETER FITTING" with parameter "FM" somewhere in the range $.95 < FM < 1.0$, then the EMTP will use all q-axis coils. Internally, however, the constraint $X'_q = FM \cdot X_q$ is observed (despite the user-punched equality of these two parameters).

b) If use is made of "PARAMETER FITTING" with parameter "FM" equal to unity ($FM = 1.0$), then the q-axis damper winding is dropped from the model; this leaves just one q-axis coil.

Case 3 : It is not uncommon for the user to have no data values for X'_q and T'_{qo}. In this case, he can still run the simulation if he does three things to the data:

1) Use "PARAMETER FITTING" with $FM = 1.0$;
2) Punch X'_q equal to the known X_q value;
3) Set (punch) $T'_{qo} = 0.0$.

In this case, the EMTP will drop the q-axis damper winding from the model, leaving just one q-axis coil.

Case 4 : Just like Case 2, only with "q" (referring to the quadrature axis) replaced by "d" (referring to the direct axis).

Case 5 : Just like Case 3 , only with "q" replaced by "d" .

Case 6 : If the user wants to model a machine without any damper windings at all on the q-axis, he is to set $X_q = X'_q = X''_q$ and $T'_{qo} = T''_{qo}$ positive. The latter assignment prevents misleading diagnostics, even though the particular positive time constant is not used by the EMTP.

Class 3 S.M. data cards

Next come either 3 or 4 cards, which specify the electrical parameters of the synchronous machine. The 1st of this group has the following format:

NUMAS	KMAC	KEXC	NP	SMOUTP	SMOUTQ	RMVA	RKV	AGLINE	S1	S2
I2	I2	I2	I4	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6

NUMAS —— The number of connected masses on the shaft system of this generator. A limit of 10 is presently imposed.

KMAC —— The mass number which corresponds to the generator (or motor) rotor, within the interconnected mass-spring shaft system. Masses are to be numbered by the user for identification, beginning with number one on either end, and continuing sequentially (2, 3, ..) to the other end of the shaft. See Figs. 3 and 4 at the very beginning of Section 1.62 ;

KEXC —— The mass number which corresponds to the exciter on the shaft system. If no exciter exists, leave this field blank.

NP —— The number of poles (not pole pairs) which characterize the machine rotor. The electrical frequency of the machine is equal to the mechanical frequency times NP / 2 , recall.

SMOUTP —— Proportionality factor which is used only to split the real power among the two halves of a dual machine during the machine initialization. If a single machine, this field may be ignored. If a dual machine, suppose that the user punches value PA for this half of the dual, and value PB for the other half; then the fraction PA / (PA + PB) of the total steady-state real power output will be assigned to this half of the dual during machine initialization.

SMOUTQ —— The same as "SMOUTP" , only for reactive rather than real power.

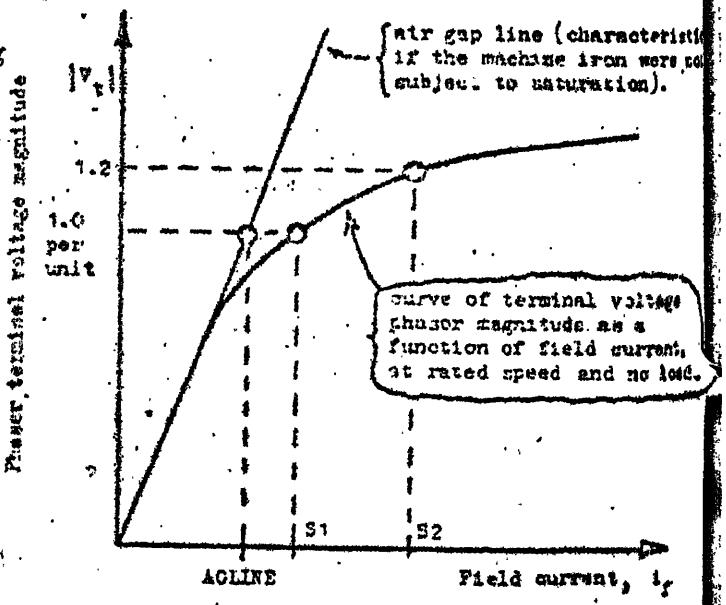
RMVA —— The total 3-phase volt-ampere rating of the machine, in units of MVA (million volt-amperes).

RKV —— The rated line-to-line voltage of the machine, in units of RMS kV . Taken as a pair, "RKV" and "RMVA" define the base values upon which per unit machine parameters are assumed to apply, it may be noted.

AGLINE —— Value of the field current in amperes which will produce rated armature voltage (1.0 per unit) on the air gap line. This is an indirect specification of the mutual inductance between the field and the armature of the machine. Se sketch below. If the S.M. is saturable, append an extra minus sign (making "AGLINE" negative) as a flag.

S1 —— Value of the field current in amperes which will produce rated armature voltage (1.0 per unit) on the no-load saturation curve. See right. This field, as well as "S2" , can be left blank if the S.M. is not saturable.

S2 —— Like "S1" , only for 120% of rated voltage (1.2 per unit).



The parameters "AGLINE" , "S1" , and "S2" just inputted actually apply to the d-axis of the machine. A second card can follow --- call it Card 1a (as an extension of Card 1) --- to provide for the same three parameters, only for the q-axis:

	AGLQ	S1Q	S2Q
	E10.6	E10.6	E10.6

If there is to be no saturation modeling for the q-axis, this card can be omitted or left blank. Nonzero values of "AGLQ" indicate saturation as follows:

AGLQ > 0 : Here the q-axis air-gap line is known, and AGLQ is the value of the field current in amperes which will produce rated armature voltage on that line. Data fields "S1Q" and "S2Q" must not be left blank (supply correct values).

AGLQ < 0 : The negative value for AGLQ is a flag indicating that the user does not know the air-gap line for the q-axis, but the user does want q-axis saturation modeling. The EMTP will proceed to internally generate an approximate value, and use it for q-axis saturation modeling. In this case, "S1Q" and "S2Q" can be left blank, and -1.0 can be used for "AGLQ" .

The remaining cards of Class 3 S.M. data depend upon whether standard manufacturer-supplied data are being used. If so (if the machine has type code 50 or 51), two additional cards having the following format complete the Class 2 data:

R_a	X_ℓ	X_d	X_q	X'_d	X'_q	X''_d	X''_q
E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6

T'_{do}	T'_{qo}	T''_{do}	T''_{qo}	X_o	R_n	X_n	INZERO
E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	I10

R_a —— Armature resistance, in per unit. Must be non-negative.

X_ℓ —— Armature leakage reactance, in per unit. If unknown, use the smallest of X_d'', X_q'', and X_o.

X_d —— Direct-axis (d-axis) synchronous reactance, in per unit.

X_q —— Quadrature-axis (q-axis) synchronous reactance, in per unit.

X_d' —— Direct-axis (d-axis) transient reactance, in per unit.

X_q' —— Quadrature-axis (q-axis) transient reactance, in per unit.

X_d'' —— Direct-axis (d-axis) subtransient reactance, in per unit.

X_q'' —— Quadrature-axis (q-axis) subtransient reactance, in per unit.

T_{do}' —— Direct-axis (d-axis) open-circuit transient time constant, in seconds.

T_{qo}' —— Quadrature-axis (q-axis) open-circuit transient time constant, in seconds.

T_{do}'' —— Direct-axis (d-axis) open-circuit subtransient time constant, in seconds.

T_{qo}'' —— Quadrature-axis (q-axis) open-circuit subtransient time constant, in seconds.

X_o —— Zero-sequence reactance, in per unit. If this is unknown, it is suggested that the same value as for X_d'' or X_ℓ be used. See note below.

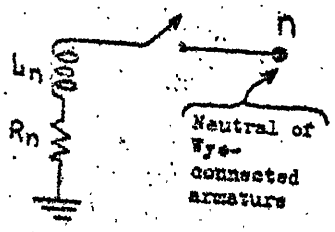
R_n —— The real part of the neutral grounding impedance, in per unit. See note below.

X_n —— The imaginary part of the neutral grounding impedance, in per unit. See note below.

Note: X_o, R_n, X_n have meaning only if the machine is Wye-connected (no "DELTA CONNECTION" card), and if variable "INZERO" below is zero or blank. Otherwise, columns 41-70 may be left blank.

INZERO —— For a Wye-connected machine, this variable signals the status of the switch in the neutral connection to ground:

$\begin{cases} 0 \Longrightarrow \text{switch closed} \\ 1 \Longrightarrow \text{switch open} \end{cases}$



On the other hand, should the user have chosen to describe the machine by means of per unit inductance and resistance matrices (machine type codes 52 or 53), then the Class 2 S.M. data is completed with three cards of the following format:

L_f	L_{af}	L_{fkd}	L_d	L_{akd}	L_{kd}
E10.6	E10.6	E10.6	E10.6	E10.6	E10.6

L_g	L_{ag}	L_{gkq}	L_q	L_{akq}	L_{kq}		INZERO
E10.6	E10.6	E10.6	E10.6	E10.6	E10.6		I10

X_0	R_a	R_f	R_{kd}	R_g	R_{kq}	R_n	X_n
E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6	E10.6

L_f —— The self-inductance of the field winding (circuit number 1 on the direct axis (d-axis) of the rotor), in per unit.

L_{af} —— The mutual-inductance coefficient between the armature and the field winding (circuit number 1 on the direct axis (d-axis) of the rotor), in per unit.

L_{fkd} —— The mutual-inductance coefficient between the field winding (circuit number 1 on the direct axis (d-axis) of the rotor) and the direct axis damper winding (circuit number 2 on the direct axis (d-axis) of the rotor), in per unit.

L_d —— The self-inductance coefficient for the direct axis (d-axis) of the armature, in per unit.

L_{akd} —— The mutual-inductance coefficient between the armature and the direct axis damper winding (circuit number 2 on the direct axis (d-axis) of the rotor), in per unit.

L_{kd} —— The self-inductance of the direct axis damper winding (circuit number 2 on the direct axis (d-axis) of the rotor), in per unit.

Note : Direct-axis parameters L_{af} , L_{fkd} , and L_{akd} are generally assumed to all be equal. But this is not a constraint of the EMTP code. Unequal values can be used, if available.

Numbering of windings on the direct axis (d-axis) :
- #1 ——— field winding of machine
- #2 ——— d-axis damper winding

Numbering of windings on the quadrature axis (q-axis) :
- #1 ——— q-axis damper winding
- #2 ——— eddy current winding

L_g ——— The self-inductance of the q-axis damper winding (circuit number 1 on the quadrature axis (q-axis) of the rotor), in per unit.

L_{ag} ——— The mutual inductance coefficient between the armature and the q-axis damper winding (circuit number 1 on the quadrature axis (q-axis) of the rotor), in per unit.

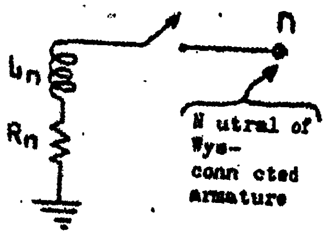
L_{gkq} ——— The mutual inductance coefficient between the two circuits on the quadrature axis (q-axis) of the rotor, in per unit.

L_q ——— The self-inductance coefficient for the quadrature axis (q-axis) of the armature, in per unit.

L_{akq} ——— The mutual-inductance coefficient between the armature and the eddy-current winding (circuit number 2 on the quadrature axis (q-axis) of the rotor), in per unit.

L_{kq} ——— The self-inductance of the eddy-current winding (circuit number 2 on the quadrature axis (q-axis) of the rotor), in per unit.

INZERO ——— For a Wye-connected machine, this variable signals the status of the switch in the neutral connection to ground:
- 0 ⇒ switch closed
- 1 ⇒ switch open



Note : Quadrature-axis parameters L_{ag}, L_{gkq} and L_{akq} are generally assumed to all be equal. But this is not a constraint of the EMTP code. Unequal values can be used, if available.

X_o —— Zero-sequence reactance, in per unit. If this is unknown, it is suggested that the same value as for X_d'' or X_ℓ be used. See note below.

R_a —— Armature resistance, in per unit.

R_f —— Resistance of the field winding (winding number 1 on the direct axis), in per unit.

R_{kd} —— Resistance of the damper winding on the direct-axis (d-axis) of the rotor, in per unit. This is the resistance of winding number 2 on the d-axis of the rotor.

R_g —— Resistance of the q-axis damper winding (winding number 1 on the quadrature axis (q-axis) of the rotor), in per unit.

R_{kq} —— Resistance of the eddy-current winding (winding number 2 on the quadrature axis (q-axis) of the rotor), in per unit.

R_n —— The real part of the neutral grounding impedance, in per unit. See note below.

X_n —— The imaginary part of the neutral grounding impedance, in per unit. See note below.

Note : X_o, R_n, and X_n have meaning only if the machine is Wye-connected (no "DELTA CONNECTION" card), and if variable "INZERO" of the preceding card is zero or blank. Otherwise, columns 1-10 and 61-80 may be left blank.

Class 4 S.M. Data cards

Next in order of data input come the mass cards which contain mechanical parameters for the shaft system. There is to be one such card for each mass, punched according to the format immediately below. In number, there are "NUMAS" such cards (see 1st card of Class 3 data, columns 1-2); ordering is actually immaterial (the mass cards can be shuffled), though it is generally clearer to stack such cards in naturally-increasing order of the mass number "ML".

ML		EXTRKS	HJ	DELDMP	DMUT	HKCO	D
I2		E10.6	E10.6	E10.6	E10.6	E10.6	E10.6

ML ——— The mass number, to be punched in the field of columns 1-2 using I2 format. Recall that masses are to be numbered by the user beginning with number one on either end of the shaft system, and continuing sequentially (2, 3, ...) to the other end. See Figs. 3 and 4 at the very beginning of Section 1.62 .

EXTRKS ——— Punched in columns 11-20 (read using E10.6 format) is to be the fraction of the total external mechanical torque which is associated with this mass:

Generator : For a generator, enter the fraction of the total external mechanical torque of this shaft system which is applied to this particular mass. If a pump, enter a negative value.

Motor : For a motor, enter the fraction of the total external mechanical torque of the shaft system which is developed by this particular mass. If a pump, enter a positive value.

A constraint on the "EXTRKS" values is that the sum of all positive entries for the shaft system must equal unity. Another constraint is that the sum of all entries must be positive.

HJ ——— The moment of inertia (WR^2) of mass number "ML" is read from the field of columns 21-30 using E10.6 format. This is to be in units of $\left[\text{million pound-feet}^2\right]$.

DELDMP ——— The speed-deviation self-damping coefficient for mass number "ML" is read from the field of columns 31-40 using E10.6 format. By definition,

$$T_i = \text{DELDMP} \; (\omega_i - \omega_s)$$

where T_i is this particular damping torque under consideration for mass number $i = \text{ML}$, ω_i is the angular velocity of mass i , and ω_s is the synchronous mechanical velocity for this shaft system. Data is to be punched in units of

$$\left[(\text{pound-feet}) \,/\, (\text{radians/second})\right]$$

DMUT ——— The mutual-damping coefficient is to be read from columns 41-50 using E10.6 format. This pertains to the present mass (assumed to be number $i = ML$) and the mass with the next higher number ($i+1$). The damping in question is a function of the velocity difference between the two masses:

$$T = \mathrm{DMUT}\cdot(\omega_i - \omega_{i+1})$$

The mutual-damping coefficient is to be punched in units of $\left[\text{(pound-feet)} / \text{(radians/second)} \right]$

HKCO ——— The spring constant is to be read from columns 51-60 using E10.6 format. This pertains to the elastic connection between the present mass (assumed to be number $i = ML$) and the mass with the next higher number ($i+1$). Units for this data are $\left[\text{(million pound-feet)} / \text{(radian)} \right]$

D ——— The absolute-speed self-damping coefficient for this mass is to be read from columns 61-70 using E10.6 format. By definition, $T_i = D\cdot\omega_i$ where T_i is the associated damping torque on mass number i, and ω_i is the angular velocity (absolute) of this mass. Units for this data are $\left[\text{(pound-feet)} / \text{(radians/second)} \right]$

It will be noted that fields "DMUT" and "HKCO" contain data which really does not belong exclusively to mass number $i = ML$; it also pertains equally to the mass which is numbered $i+1$. For mass card of the highest-numbered mass (number "NUMAS"), then, these two fields have no meaning, and are to be left blank.

Class 5 S.M. Data Cards

Next in order of data input comes a single output-variable specification card, which is to be punched according to the format described immediately below. Only those synchronous machine variables which are explicitely requested for output using this card will be a part of the EMTP output vector, which is used for both printing and plotting. The request scheme, unless otherwise noted below, is:

"0" —— leave blank, or punch a zero, if no such output is desired;
"1" —— punch unity for output in per unit;
"2" —— punch two for output in physical units.

1	2	3	4	5	6	7	8	9	10	11	12	13	13+LIMASS	13+2*LIMASS ....
JPAR	JMIC	JIDQO	JFI	JD2	JQ1	JQ2	JFV	JETM	JETE	JIABC	JSAT	Angles θ_i $1 \leq i \leq$ LIMASS	Speeds ω_i $1 \leq i \leq$ LIMASS	Torques T_i $1 \leq i \leq$ LIMASS-1
I1	I1	I1	I1	I1	I1	I1	I1	I1	I1	I1	I1	all I1	all I1	all I1

JPAR 1 —— Controls printout of the machine inductances and resistances, plus the mechanical data of the shaft system, during the steady-state initial-condition printout. This is available in per unit only (a "2"-punch will not be honored). Mneumonically, the "PAR" of the name "JPAR" comes from "parameter".

JMIC 2 —— Controls printout of the initial conditions for this synchronous machine, which are based on the EMTP steady-state phasor network solution. Mneumonically, the "MIC" of the name "JMIC" comes from "machine initial conditions".

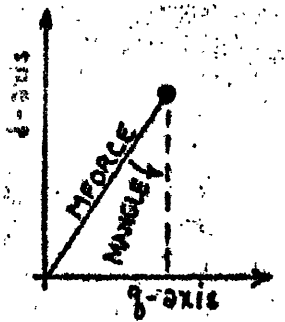
JIDQO 3 —— Controls printout of the armature currents in d-q-o coordinates (rotating reference frame), within the time-step loop. Mathematically, the notation used for these variables is i_d , i_q , and i_o ; the EMTP names which are used for output identification are (all A6 format) "ID ", "IQ ", and "IO ". See also col. 41.

JFI 4 —— Controls printout of the current in the field winding of the machine (circuit number 1 on the direct axis). Mathematical notation for this is i_f ; the EMTP name which is used for output identification is "IF ".

JD2 5 —— Controls printout of the current in the damper winding of the direct axis (d-axis) of the machine. The winding in question is winding number 2 on the d-axis. Mathematical notation for the current is i_{kd} . the EMTP name which is used for output identification is "IKD ".

JQ1 6	Controls printout of the current in the q-axis damper winding (circuit number 1 on the quadrature axis (q-axis) of the rotor). Mathematical notation for this current is i_g ; the EMTP name which is used for output identification is "IG ".
JQ2 7	Controls printout of the current in the eddy-current winding (circuit number 2 on the quadrature axis (q-axis) of the rotor). Mathematical notation for this current is i_{kq} . the EMTP name which is used for output identification is "IKQ ".
JFV 8	Controls printout of the voltage which is applied to the field winding by the exciter. This will be a constant (dc) voltage, unless the user explicitely specifies a connection to TACS exciter dynamics as part of the Class 6 S.M. data cards to follow. The field winding is winding number 1 on the direct axis (d-axis) of the machine. Mathematical notation for the variable in question is v_f ; the EMTP name which is used for output identification is "VF ".
JBTM 9	Controls printout of the net externally-applied torque on the machine rotor. This will equal the electromechanical torque of the machine, except in cases where there is also an external mechanical torque which is applied directly to the machine rotor (e.g., the case of a single-mass representation for the shaft system). More precisely, it is $T_m - T_e$ which is printed out . The EMTP name which is used for output identification is "TQ GEN" . The sign convention is such that this torque will normally be positive for a generator (in the steady state).
JBTE 10	Controls printout of the net externally-applied torque on the exciter rotor. This will equal the electromechanical torque of the exciter, except in unusual cases where there may be an external mechanical torque applied to the exciter rotor. The EMTP name which is used for output identification is "TQ EXC" . The sign convention is such that this torque will normally be positive for a generator operating in the steady state.
JIABC 11	Controls printout of the machine armature currents in phase coordinates (actual coil variables), within the time-step loop. Mathematically, the notation used for these variables is i_a , i_b , and i_c ; the EMTP names which are used for output identification are (all A6 format) "IA ", "IB ", and "IC ". See also variable "JIDQC" of column 3, which also provides for armature current output, only in d-q-0 coordinates.

JSAT 12 —— Controls the printout of the machine flux; or more precisely, of the magnetomotive force (MMF) which drives it. If this output is selected, two EMTP variables are produced: one for the magnitude of the flux, and the other for the angle (see sketch at left). The EMTP names which are used for output identification of these variables are "MFORCE" (in ampere-turns or per-unit) and MANGLE (in degrees or radians; radians is per unit), respectively.



θ_i —— The I1 field of column 12 + i controls printout of the mechanical angle θ_i of mass number i , for i being a positive integer which does not exceed "LIMASS" .

For a definition of "LIMASS" , see one paragraph below.

The "1"-punch for per unit will produce radians, while the "2"-punch for physical units will produce degrees (as the units for this output). The angles in question are all measured with respect to a synchronously-rotating reference frame; they will be constant, then, for the case of a machine which is operating in the sinusoidal steady-state. For an unloaded machine which is operating in the steady state with no externally applied torques and no losses, all angles would equal -90 degrees. The EMTP name which is used for output identification of the angle θ_i of mass I is "ANG I " .

For example, the name associated with the angle of mass number nine is "ANG 9 " , while that for mass number thirteen is "ANG 13" .

"LIMASS" is the program limit on the number of mass s, as determined by FORTRAN dimensioning of the EMTP. Unless altered locally by Program Maintenance (for instructions, see the end of Section 1.62), this will be equal to 10 .

ω_i —— The I1 field of column 12 + LIMASS + i controls printout the angular velocity ω_i of mass number i , for i being a positive integer that does not exceed "LIMASS" . Thi output is simply the derivative of the corresponding θ_i which has been described in more detail immediately above. The "1"-punch for per unit will produce radians/sec ; while the "2"-punch for physical units will produce degrees/sec (as the units for this output). The EMTP name which is used for output identification of the mechanical angular velocity ω_i of mass I is "VEL I " .

$T_{i,i+1}$ —— The I1 field of column 12 + 2*LIMASS + i controls printou of the torque on the shaft which connects mass number i with mass number i+1 , for i a positive integer that does not exceed one less than "LIMASS" . The EMTP name which is used for output identification of the shaft torque in question (between mass i and mass i+1) is "TOR I " . The "2"-punch will give pound-feet .

For EMTP output and plotting purposes, the just-delineated output variables are actually identified by a pair of 6-character names. The second name (lower name of printed pair) identifies the variable type mneumonically, as documented above. The first name (upper name of printed pair) identifies the generator in question, in order of data input. For example, "MACH 3" would be for the third machine (assumed here to be a single), while "MAC 2B" would be for part "B" of the second machine (here assumed to be a dual, for purposes of illustration). A specific example of such column headings of printed EMTP time-step-loop output follows:

```
COLUMN HEADINGS FOR THE  28  EMTP OUTPUT VARIABLES FOLLOW.   THESE ARE ORDERED ACCORDING TO THE FIVE
POSSIBLE EMTP OUTPUT-VARIABLE CLASSES, AS FOLLOWS ....
  FIRST  12  OUTPUT VARIABLES ARE ELECTRIC-NETWORK NODE VOLTAGES (WITH RESPECT TO LOCAL GROUND)!
   NEXT   0  OUTPUT VARIABLES ARE BRANCH VOLTAGES (VOLTAGE OF UPPER NODE MINUS VOLTAGE OF LOWER NODE)!
   NEXT   3  OUTPUT VARIABLES ARE BRANCH CURRENTS (FLOWING FROM THE UPPER EMTP NODE TO THE LOWER)!
   NEXT  13  OUTPUT VARIABLES PERTAIN TO DYNAMIC SYNCHRONOUS MACHINES, WITH NAMES GENERATED INTERNALLY!
  FINAL   0  OUTPUT VARIABLES BELONG TO  'TACS'  (NOTE INTERNALLY-ADDED UPPER NAME OF PAIR).
BRANCH POWER  CONSUMPTION (POWER  FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH VOLTAGE FOR THIS GROUPING!
BRANCH ENERGY CONSUMPTION (ENERGY FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH CURRENT FOR THIS GROUPING.

 STEP    TIME        C2          B2          A2          A3          C3          B3          A1          B1          C1

                     A4          B4          C4          A1          B1          C1          MACH 1      MACH 1      MAC
                                                         A2          B2          C2          ID          IQ          I0

                     MACH 1      MACH 1      MACH 1      MACH 1      MACH 1      MACH 1      MACH 1      MACH 1      MAC
                     IF          IKD         IG          IKQ         TQ GEN      IA          IB          IC          ANG

                     MACH 1
                     VEL 1
```

Alternate expanded format for Class 5 S.M. data

An alternate format to that which has just been presented for Class 5 S.M. data is available. It is less compact (usually requiring two cards rather than just one), but is more flexible in some ways, as shall now be explained.

First there is to appear one card which bears a 6-character key word, plus the first eleven variables of the original compact format:

TEXT		JPAR	JMIC	JIDQQ	JFI	JD2	JQ1	JQ2	JFY	JETM	JETE	JIABC	JSAT
A6		I5	I5	I5	I5	I5	I5	I5	I5	I5	I5	I5	I5

TEXT ——— 6-character key word, for which there are the
1-6 following three options:

"ALL " —— if all possible shaft variables (angles, velocities, and inter-mass torques) are to be outputted. All such shaft outputs will either be in physical units, or all will be in per unit; a mixture is not possible, when using "ALL" . The units to be used will agree with the right-most nonzero punch on the card. For example, there will be agreement with the "JIABC" choice, if column 65 is punched nonzero.

"NONE" —— if no possible shaft variables are to be outputted.

"EXTEND" —— if selective output of shaft variables is desired, as specified on an extension (continuation) card to follow.

All other variables on the card (beginning with "JPAR" of columns 11-15) have exactly the same meaning as previously; they shall not be defined again here.

If "TEXT" (see above) were punched equal to "NONE " or "ALL " , then the just-described card would constitute all of the Class 5 S.M. data. But should "EXTEND" be punched instead, then a second data card must follow, to define the desired shaft output quantities:

..... LIMASS	....2*LIMASS	....3*LIMASS-1
Angles θ_i $1 \leq i \leq$ LIMASS	Speeds ω_i $1 \leq i \leq$ LIMASS	Shaft torques T_i $1 \leq i \leq$ LIMASS-1
all I1 format	all I1 format	all I1 format

The meaning of all quantities as used here is exactly the same as before.

Class 6 S.M. Data Cards

Next in order of data input come cards which describe any interface connections between the machine under consideration, and TACS. The general format for the one or more such cards of Class 6 is as follows:

KK	BUS
I2	A6

Rule 1 : If the field voltage of the machine is to be controlled by exciter dynamics which have been modeled using TACS, then the following is required:

KK —— Punch "71" in columns 1-2, as a special request for the exciter connection.

BUS —— The 6-character name of a TACS variable is to be punched in columns 3-8. The numerical value of this TACS variable will then be used by the EMTP logic for the field voltage v_f of this machine. The TACS signal must be in per unit .

If no such card is used, the EMTP logic will simply hold the field voltage for this machine constant, at whatever value was dictated by the initial conditions.

Rule 2 : If the total externally-applied torque on the shaft system is to be controlled by dynamics which are modeled using TACS, then the following card is required:

KK ---- Punch "72" in columns 1-2, as a special request for the TACS control of mechanical torque.

BUS ---- The 6-character name of a TACS variable is to be punched in columns 3-8. The numerical value of this TACS variable will then be used by the EMTP logic as a multiplicative factor for scaling the otherwise-constant (steady-state) torque values.

Should the user want to code the logic of this TACS connection, but temporarily bypass any associated dynamics, he can use the name "UNITY " . Recall that this is the name of the built-in TACS source which has output identically equal to 1.0 .

If no such card is used, the EMTP logic will simply hold the external mechanical torques on the rotor masses constant (at whatever values were dictated by the initial condition calculation).

Rule 2a : If the field voltage $v_f(t)$ and/or the field current $i_f(t)$ is to be passed into TACS from the machine, then the following is required. There can be either zero, or one, or two such cards:

KK ---- Punch "73" in columns 1-2 for field voltage v_f .
Punch "74" in columns 1-2 for field current i_f .

BUS ---- The 6-character name of the TACS source whose value is to be equal to the field voltage or current at each time step.

Rule 3 : If one or more mechanical angles θ_i , angular velocities ω_i , or shaft torques T_i of the shaft system of the machine are to be passed into TACS then one data card must be punched for each such variable. Angles are in units of absolute radians (e.g., increasing by $2\pi f$ every second for 60Hz steady-state operation), angular velocities are in per unit (e.g., 1.0 for the steady-state), and shaft torques are in per unit . The data card format is:

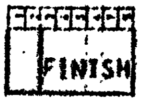
KK ---- The EMTP reads from columns 1-2 a code number which identifies the mechanical variable in question:

$$\begin{cases} \text{for } \theta_i , & \text{punch } i \\ \text{for } \omega_i , & \text{punch LIMASS} + i \\ \text{for } T_i , & \text{punch } 2\text{*LIMASS} + i \end{cases}$$

BUS ---- The EMTP reads from columns 3-8 a 6-character alphanumeric name This field is to be punched with the name of the TACS source whose value is to be controlled by the machine variable in question.

Rul 4 : Ordering of the different possible cards which have just been described is immaterial; they can b shuffled, without altering the result.

Rule 5 : The end of all such cards as have just been described is to be indicated by a special terminator card. Field "KK" is to be left blank, and field "BUS" is to be punched with the special word "FINISH" . Should this machin have no connections at all to TACS, then this "FINISH" record alone makes up the Class 6 S.M. data.



Class 7 S.M. Data cards

If the machine in question is a single (not a dual) machine, then there is no Class 7 S.M. data. In this case, the "FINISH" card of the Class 6 data represents the final data card for this dynamic synchronous machine component

But if the machine component in question is a dual machine, then Class 7 data is to consist of data cards applicable to Part B of the dual machine. Class 3 through 6 data as previously outlined belongs to Part A of the dual; Class 7 data then is a repeat of Classes 3 through 6, only as applicabl to Part B of the dual. Actually, although this makes no mention of the optional Class 2 data, such may in certain cases be applicable. For example, the Part B data can (and often will) very legitimately begin with a "PARAMETER FITTING" car of Class 2 —— before the Class 3 data. But the other possible Class 2 data ca will not normally be used. Recall that the user has been warned not to use the "DELTA CONNECTION" option for a dual machine; and the "TOLERANCES" option really only has meaning for the whole data case viewed as a single entity (so presumably would not be defined along with Part B, since Part A will come first, and will provide for a more logical positioning).

Sample EMTP S.M. Data Listings

As a first example of EMTP S.M. data input (as set up in accord with the previously-outlined rules), consider a single machine for which standard manufacturer-supplied data is available (type code 50). This example is used in Ref. 15, and comes originally from reference number 53 of that publication (from A. Charlton and G. Shackshaft, "Comparison of Accuracy of Methods for Studying Stability, Northfleet Exercise," Electra, No. 23, July 1972, pages 9-49). This example is for a real machine, then, rated at 150 MVA and 13.8 kV, with the neutral connection of the Wye solidly grounded ($R_n = X_n = 0$). The quadrature axis of the rotor is assumed to have only one winding, so this illustrates the procedure by which the user may employ a lower-order model. Note the "PARAMETER FITTING" card with parameter FM = 1.0 , plus the relations $X'_q = X_q$ and $T'_{qo} = 0$. The shaft system consists of just a single mass, and there is no connection to TACS for either exciter or governor representation. The "TOLERANCES" card actually has no effect, since for execution on CDC (as this case was originally tested by Vladimir in April of 1977), parameters are merely being redefined to their original (default) values.

```
50A1          11.3901       50.0      -30.0
  B1         |Va|           f(H3)     θa (degrees)
  C1
TOLERANCES     1.E-16       1.E-15     1.E-16
PARAMETER FITTING                1.0
 1 1    2      1.0          1.0       150.0       13.8    -600.0     680.0      890.
                                                           -1.0
   0.0014     0.175         1.85       1.76      0.2575     1.76      0.16       0.18
  5.74757               0.051142   0.382609   0.197985
 1             1.0          50.0       1.0                           1.0
EXTEND          1     1     1     1     1     1     1     1     1     1     1
1        1        1
  FINISH
```

For the record, it might be reasonable to also list the machine parameters in mathematical notation. For this case, we have:

R_a = .0014 p.u. X_ℓ = .175 p.u. X_d = 1.85 p.u.

X'_d = .2575 p.u. X''_d = .18 p.u. T'_{do} = 5.74757 sec

T''_{do} = .051142 sec AGLINE = -600 amp X_q = 1.76 p.u.

X'_q —— originally unknown. for EMTP data purposes this was punched equal to X_q , in conjunction with the "PARAMETER FITTING" request. This signals to desire to use a model with only one q-axis rotor coil, recall.

X''_q = .18 p.u. T'_{qo} = 0.0 —— also part of the "PARAMETER FITTING" choice.

T''_{qo} = .382609 sec X_o = .197985 p.u.

A field current of 600 amps will produce at rated speed 1.0 per unit voltage on the air gap line. This is the absolute value of AGLINE . The minus sign signals d-axis saturation, with 680 amps = S1 giving rated voltage, and 890 amps = S2 giving 120% of rated voltage on the no-load saturation curve. The value of AGLQ = -1.0 on the following card indicates that q-axis saturation is wanted, though data is not available (so the EMTP is to generate it internally, approximately).

As a second example of EMTP S.M. data, consider the Navajo machine as it was represented in Reference 18. The full problem has been preserved as UTPF Test Case #90, from which the following records have been extracted for purposes of illustration:

```
50GEN   A  21229.     60.0        -44.896562
 GEN    B  |Va|       f(H3)          θa
 GEN    C
TOLERANCES     1.E-16      1.E-15      1.E-16
 6 5 6      .0      1.0        892.4       26.0      1970.

           0.13      1.79       1.71       0.18977   0.40024   0.13504   0.20029
3.24906    0.35962   0.0423816  0.11782    0.130
 1         0.30      0.027691   0.0        0.0       33.68816
 2         0.26      0.046379   0.0        0.0       60.95910
 3         0.22      0.255958   0.0        0.0       90.81823
 4         0.22      0.263573   0.0        0.0       123.66340
 5                   0.258887   0.0        0.0       4.925036
 6                   0.0101995  0.0        0.0
11          1 1                 1     11111
 FINISH
```

In mathematical notation, the following electrical parameters will be seen to have been used:

R_a = 0.0 $\qquad X_\ell$ = .13 p.u. $\qquad X_d$ = 1.79 p.u.

X'_d = .18977 p.u. $\qquad X''_d$ = .13504 p.u. $\qquad T'_{do}$ = 3.24906 sec

T''_{do} = .11782 sec $\qquad X_q$ = 1.71 p.u.

X'_q = .40024 p.u. $\qquad X''_q$ = .20029 p.u. $\qquad T'_{qo}$ = .35962 sec

T''_{qo} = .13 sec $\qquad X_o$ = .13

The armature is Wye-connected, with the neutral solidly grounded (i.e., $R_n = L_n = 0$). The machine model has the full seven windings ---- the three armature windings, plus two on each axis of the rotor. This is a two-pole (3600-rpm) machine.

The rotor shaft system consists of six masses, with the generator rotor being numbered "5" and the exciter "6". The total external mechanical torque is divided among the six masses according to the following fixed proportions:

Mass number	1	2	3	4	5	6
fractional torque	.30	.26	.22	.22	0.0	0.0

The moments of inertia of the rotor masses are as per the following tabulation, in units of million pound mass - feet^2 :

.02769	.04637	.25595	.26357	.25888	.010199

There is no mechanical damping at all in this problem ---- neither absolute-speed, nor speed-deviation, nor mutual damping.

The five springs which interconnect the six masses of the shaft system have the following spring constants, in units of million pound force - feet / radian. :

Masses connected	1, 2	2,3	3,4	4,5	5,6
Spring constant	33.68816	60.95910	90.8182	123.6634	4.925036

The 3-phase base power of the generator is 892.4 MVA , and the base voltage (line to-line) is 26.0 kV (rms).

A field current of 1970 amps will produce at rated speed 1.0 per unit voltage on the air gap line.

The iron of the machine is assumed to be linear (there is no saturation modeling, since AGLINE = 1970 is positive, and the following data card is blank.

As a third example of EMTP synchronous machine data, consider a dual machine in which the first half has a connection to TACS. This is part of UTPF Test Case #87. The two halves of the dual are identical, as documented on the following data cards:

```
53  GENA   21228.9  60.          -22.10
    GENB   |Va|      f             θa                      grounding
    GENC                                                   switch
TOLERANCES     1.E-16     1.E-15    1.E-16                 open
 9 5 8   2                          710.      26.      2000.

    1.624      1.505      1.505     1.726     1.505     1.546
    100.       1.505      1.505     1.725     1.505     1.567          100.
    15         .0264      .00085    .0119     1.0       .0119
 1             .2747      .01466               911.36   135.26
 2              2705      .0326               1114.68   192.04
 3             .2274      .1799              10064.     179.09
 4             .2274      .1799               1118.22    84.48
 5                        .221               12623.     118.91
 6                        000768              1193.45   170.19
 7                        .00787              1193.45    56.71
 8                   .00391                      1193.45    42.39
 9                   000675
111      1 1  2 6      1       1 11111  2
71VFLD   }
72UNITY  }  TACS interface quantities for Part "A" of dual        "A"
 3ANG 3  }
13VEL 3  }
  FINISH
 9 5 8   2                       710.       26.        2000.

   1.624      1.505      1.505      1.726      1.505      1.546
   100.       1.505      1.505      1.726      1.505      1.567
   .15        .0264      .00085     .0119      1.0        .0119      "B"     100.
1             .2747      .01466                911.36     135.26
2             .2705      .0326                 1114.68    192.04
3             .2274      .1799                 10064.     179.09
4             .2274      .1799                 1118.22    84.48
5                        .221                  12623.     118.91
6                        .000768               1193.45    170.19
7                        .00787                1193.45    56.71
8                        .00391                1193.45    42.39
9                        .000675
111      1 2  2            1         11111
 FINISH
```

In mathematical notation, the following electrical parameters will be seen to have been used for each half of the dual:

R_a = .0264 p.u. R_f = .00085 p.u. R_g = 1.0 p.u.

R_{kd} = R_{kq} = .0119 p.u.

L_{af} = L_{ag} = L_{akd} = L_{akq} = L_{fkd} = L_{gkq} = 1.505 p.u.

L_d = L_q = 1.726 p.u.

L_o = 0.15 p.u. L_f = 1.624 p.u. L_g = 100. p.u.

L_{kd} = 1.546 p.u. L_{kq} = 1.567 p.u.

The armature is Wye-connected, with the impedance of the neutral connection being 100 p.u. reactance; but since the grounding switch is open, the effective neutral impedance is infinite. The machine has two poles (synchronous mechanical speed is 3600 rpm).

The machine has a full seven windings (four on the rotor). But the g-winding (winding number 1 on the quadrature axis of the rotor) seems to be artificially created; parameter values are such that it's influence is minimal.

The 3-phase base power of the generator is 710 MVA, and the base voltage (line-to-line) is 26.0 kV (rms).

A field current of 2000 amps will produce at rated speed 1.0 per unit voltage on the air gap line. There is no magnetic saturation, for either axis.

The shaft system consists of 9 masses, of which number 8 is the exciter and number 5 is the generator rotor.

There is no self damping of the masses ---- neither absolute-speed nor speed-deviation; but there is mutual damping, as shown in the second column of the tabulation below. The first column gives the mechanical moment of inertia; the third column gives the spring constant; and the fourth column gives the fraction of the total externally-applied mechanical torque which reaches each mass.

Mass #K	HJ(K) inertia $10^6 lb_m-ft^2$	DMUT(K) mutual damping lb_f-ft-sec/rad	HKCO(K) spring const. $10^6 lb_f$-ft/rad	EXTRKS(K) fractional torque
1	.01466	911.36	135.26	.2747
2	.0326	1114.68	192.04	.2705
3	.1799	10064.00	179.09	.2274
4	.1799	1118.22	84.48	.2274
5	.2210	12623.00	118.91	0.0
6	.000768	1193.45	170.19	0.0
7	.00787	1193.45	56.71	0.0
8	.00391	1193.45	42.39	0.0
9	.000675			0.0

It will be noted that four connections to TACS have been specified:

a) The voltage which is to be applied to the field winding of the rotor is given numerically by a TACS variable named "VFLD ". This would be the output of an exciter, which had been previously defined as per the Section 8. rules.

b) The scaling factor for the total external mechanical torque is given numerically by the TACS variable which has name "UNITY ". Recall that "UNITY " is a built-in TACS source which always has value 1.0 , so this TACS connection really has no effect (it could be omitted without affecting the result of the simulation).

c) The angle of mass #3 is being passed to TACS as the numerical value of the TACS source which has name "ANG 3 ". TACS data must include a Type-92 source with this name, then.

d) The angular velocity of mass #3 is being passed to TACS as the numerical value of the TACS source which has name "VEL 3 " TACS data must include a Type-92 source with this name, then

How to Increase the Limits on Masses, Generators, Output Variables

As of April of 1980, the SCE EMTP S.M. code is still fixed-dimension, with array storage much as originally supplied by SCE. But various changes have been made within the body of the code so that the alteration of such fixed limits is now straightforward and simple. It is the purpose of the present section to document how the dimensioned limits for masses, generator busses, and S.M. output variables can be changed by Program Maintenance, should this prove to be necessary.

First, consider the role of List #17 of EMTP variable dimensioning (see Section 0.6). From this the user might get the idea that the S.M. code is already variably-dimensioned. But this is not so! Only the interface vectors with the electric network have been so made flexible. The S.M. code proper remains fixed-dimension, which forces the user to be consistent. The number of dynamic S.M.s as requested in List #17 must always equal the number for which the machine code proper has been dimensioned by Program Maintenance. If not, execution will be terminated during the S.M. data input (UTPF overlay number 5) by means of a special temporary "STOP" statement. See Message 42 of Section 7.2b .

In order to change the maximum number of dynamic S.M. EMTP source components, Program Maintenance need only increase the appropriate dimensions of numerous arrays which are contained in the labeled common block which is named /SMACH/ . A so-called "dual machine" is really two machines, in terms of this counting. Using the notation where letter "G" signifies the number of individual machines, a dual then contributes two. For example, to allow for a maximum of 3 dual machines and 4 single ones, one needs "G" to equal or exceed 3 * 2 + 4 = 10 . This same dimensioning (G=10) would also allow the running of problems with 10 single machines and no duals, or 5 dual machines and no singles. I.e., it is only the total number of individual machines which is constrained, thanks to a recent modification by Vladimir. As of April of 1980, the UTPF (with "M27." idents) has G = 4 .

A similar statement can be made for a change in the maximum number of masses which are part of the shaft system of each dynamic S.M. in the system. Using "M" to signify the maximum number of masses, it is seen that some arrays use just "M" while others use twice this figure ("2M") . Array "ISMOUT" is the gross exception, with the first subscript "S" being equal to S = 3M + 12 . See also two paragraphs below, for a final qualification. Then too, it might be appropriate to give a word of caution about simulations which involve machines with a large number of connected masses : one component of the numerical solution effort for each time step depends on the square of the number of masses. For large numbers of masses (e.g., 40 or 50), this should dominate, and total problem solution speed should be choked down accordingly. Note also that total storage requirements have a component which is proportional to the square of the dimensioned limit for masses. Hence, use moderation when increasing the dimensioned limit on the number of rotor masses of dynamic S.M.s .

A final fixed dimension of the S.M. code which the user might want to alter is the maximum number of S.M. output quantities (the total for all dynamic S.M.s of the problem). In the list below, this dimension has been denoted by "P" ; in the Fall of 1977, the UTPF had P = 75 .

Arrays "AMACH" , "A1MACH" , and "TEMP" are shown in the tabulation below as being dimensioned "2M" , which is correct as long as the maximum number of masses "M" is greater than or equal to seven. But for M < 6 , the "2M" subscript of these three arrays must be changed to 14 .

It might be mentioned that all appearances of the labeled common block /SMACH/ are identical in every respect. This is because all come from the same master copy, using an exact card-image reproduction. Hence, if one is searching for such records using the editor software of a computer system which does not have "deck" capability (e.g., IBM, Honeywell, G.E. Mark III, or Telefunken, as of October, 1977), he can count on fixed, absolute column positioning of all characters. At least this will be the situation with the EMTP FORTRAN as generated by translation (E/T execution) of the UTPF; if local Program Maintenance should upset this property for some reason, that's their problem!

Ok, so here is the long-awaited listing of variables which make up COMMON /SMACH/ , in order of their FORTRAN appearance:

```
COMMON  /SMACH/  BUSSM(P  ),  BUSSMA(G )
COMMON  /SMACH/  SBVA(G ) , SBVOLT(G ) , SBOMGA(G ) , SBCUR(G )
COMMON  /SMACH/  SBTIME(G ) , SBIMPD(G ) , SBIND(G )
COMMON  /SMACH/  RA(G ), RF(G ) , RKD(G ) , RG(G ) , RKQ(G )
COMMON  /SMACH/  RN(G ) , ELF(G ) , ELAF(G ) , ELFKD(G ) ,ELN(G )
COMMON  /SMACH/  ELD(G ) , ELAKD(G ) , ELKD(G ) , ELG(G )
COMMON  /SMACH/  ELAG(G ), ELGKQ(G )
COMMON  /SMACH/  ELQ(G ) , ELAKQ(G ) , ELKQ(G ),ELO(G )
COMMON  /SMACH/  FBVOLT(G ) , FBCUR(G ) , FBIMPD(G ) , FBIND(G )
COMMON  /SMACH/  FBMUT (G ), BTORK(G ), VSMTOR(G )
COMMON  /SMACH/  BINERT(G ) , BDAMP(G ) , EXTRKS(M ,G )
COMMON  /SMACH/  HJ(M ,G ) , D(M ,G ) , DMUT(M ,G ) , HKCO(M ,G )
COMMON  /SMACH/  SMOUTP(G ) , SMOUTQ(G )
COMMON  /SMACH/  AGLINE(G ) , SAT10(G ) , SAT12(G )
COMMON  /SMACH/  DELOMP(M ,G )
COMMON  /SMACH/  TORQ(M ,G ) , THETA(M ,G ) , OMGA(M ,G ), U(7,G )
COMMON  /SMACH/  EOLD(7,G ) , TGM(G ), OMGANU(G ), TEXM(G )
COMMON  /SMACH/  E11(M ,M ,G ) , E12(M ,M ,G ) , E21(M ,M ,G )
COMMON  /SMACH/  E22(M ,M ,G ) , COEF(6,6,G )
COMMON  /SMACH/  AD1(G ) , AD2(G ), AD3(G ) , AD4(G )
COMMON  /SMACH/  AD5(G ) , AQ2(G ) , AQ4(G ) , AQ5(G )
COMMON  /SMACH/  SMOUTV(P  )
COMMON  /SMACH/  ZAA, ZAB, ZAC, ZBA, ZBB, ZBC, ZCA, ZCB, ZCC
COMMON  /SMACH/  VA, VB, VC, Z11, Z12, Z13, Z21, Z22
COMMON  /SMACH/  Z23, Z31, Z32, Z33,  V1, V2, V3
COMMON  /SMACH/  TEMP(2M),  AXP(2M,2M)
COMMON  /SMACH/  AMACH(2M,2M),  A1MACH(2M,2M)
COMMON  /SMACH/  PARKZ(3,3,G ), PARKV1(2), PARKV2(2)
COMMON  /SMACH/  PARKV3(2), GAUCHE(196), RHS(14)
COMMON  /SMACH/  SQRT3,THTW,ASQRT3,ATHTW,FLTEXT(800)
COMMON  /SMACH/  NSMOUT, LIMASS, NSMBUS, MFIRST
COMMON  /SMACH/  KSUBSM, INTEXT(12)
COMMON  /SMACH/  KSMOUT(P ), JSMOUT(P ), ISAT(G )
COMMON  /SMACH/  ISMOUT(8 ,G ), IMDUAL(G ), JASMIT(G )
COMMON  /SMACH/  NUMAS(G ) , KMAC(G ) , KEXC(G ), ICONFG(G )
COMMON  /SMACH/  NP(G ) ,JEXCIT(G ), JSMTOR(G ), INZERO(G )

 DIMENSION AMSAT(20), ASAT(50)
```

A final temporary complication or qualification exists, due to the sharing of the aforementioned COMMON /SMACH/ space by the Section 1.62n Brandwajn-Dommel S.M. code. The theory of this alternative formulation is covered in References 14-15 . First there is an array FLTEXT(800) , which is inserted in /SMACH/ just before the beginning of INTEGER variables, in order to reserve more working space. Then, below the equivalence which involves BUSSM(1) (see the last record of the listing above), there will be found various extra DIMENSION and EQUIVALENCE statements. All of these can remain unaltered during any increase in one or more dimensions of the SCE S.M. code. As for the decrease of one or more S.M. dimensions, beware that one or more Brandwajn-Dommel S.M. equivalences might possibly be illegal on some computer systems It is not recommended that any SCE S.M. dimensions be decreased, except possibly after a thorough scrutiny of all arrays.

1.63 UNIVERSAL MACHINE (U.M.) DYNAMIC SOURCE COMPONENT

The universal machine (U.M.) is an EMTP source by component classification. It provides for the dynamic representation of a wide variety of rotating electromechanical energy converters:

1. synchronous machines (1, 2, or 3-phase armatures, with various rotor configurations and connections;
2. induction machines (1, 2, or 3-phase);
3. dc machines (with various field connections).

The feature was developed by Prof. Hian Lauw of Oregon State University in Corvallis, under contract with BPA (see address below).

The EMTP user is advised not to use U.M. modeling without a good reason, however! For the representation of a conventional 3-phase power system generator, the user is generally advised to employ the production S.M. modeling of Section 1.62 . The S.M. code is more fully developed, better tested, more efficient numerically, and of greater convenience for the typical "conventional" problem. But there are many less-typical applications for which the U.M. is recommended, for a number of reasons:

a) The U.M. is variably dimensioned. The user can have as many machines and as many masses as he wants.
b) The U.M. can represent new machine types, such as induction (asynchronous) machines and dc machines.
c) The U.M. offers more modeling flexibility for synchronous machines. An arbitrary number of rotor coils on each axis is allowed, as is an arbitrary number of masses, without any numerical problem or penalty. The connection of machine coils to TACS and the electric network is also more general.

So, if any such flexibility appears attractive, read on!

The universal machine is still just in its infancy, and user documentation is less than complete and coordinated at this time (mid-May, 1980). Hian, working under considerable time pressure, has just supplied 13 pages of typed rules, which appear as Section 1.63B . In case of doubt or conflicts, Section B should provide the final word, then. But it is the conventional 3-phase induction motor which is expected to be modeled most, and Section 1.63A has been devoted just to it (pages TPIM-2 through 13 of Ref. 8, Vol. X, 15 April 1980). On the other hand, because there always seems to be a shortage of illustrations, and because there is inevitable interest in three-phase synchronous machine modeling, Section 1.63C illustrates such an application (pages SRFH-3 through 11 of Ref. 8, Vol. X, 9 Apr 1980).

A second contract with Hian is in the final stages of negotiation. This should keep Hian associated with EMTP use and U.M. modeling for twelve months, though May or June of 1981. If there are problems with U.M. usage, then, Hian should be available to correct any bugs (though the contract actually involves study of the capacitively-excited induction wind generator). I encourage serious users who are having problems with U.M. usage to contact Hian while he is still available to support what he has written. We at BPA (Tsu-huei and Scott) will be in touch with him, so that an initial inquiry here is not unreasonable. But to contact Hian directly, use his Corvallis address:

Dr. Hian Lauw, Professor
Electrical & Computer Engineering Department
Oregon State University
Corvallis, Oregon 97331
U.S.A. phone: (503) 754-3617

1.63A Three-Phase Induction Machine Application of the U.M.

TPIM-2

(II) USER INSTRUCTIONS FOR U.M. MODELING OF INDUCTION MACHINE

A. Data Applicable to the Problem as a Whole

The U.M. tables are stored within the total allocation of Lis 25 of EMTP variable dimensioning. Make sure that the EMTP has been link-edited (loaded) with non-unity storage for this working area. Recall that the first line on page SRFH-5 showed 317 cells used fo that synchronous machine of the first test. Having a fully virtual machine (the VAX) at BPA, we are overlay generous, and will never hav a problem (3700 cells are presently allocated).

The first data card belonging to the U.M. is a request for the allocation of List 25 storage among Hian's four different tables. This card must precede the miscellaneous data cards, and should follo the BEGIN NEW DATA CASE card that begins the data case. Within thos limits, ordering is immaterial (all such special-request cards at the front can come in any order). Using free-format, we have:

```
         1         2         3
123456789012345678901234567890123
ABSOLUTE U.M. DIMENSIONS, I, J, K, L
```

where "I", "J", "K", and "L" are symbols for explicitely-punched integers having the following meaning:

I --- maximum total number of coils (for all machines)
J --- maximum number of machines
K --- maximum number of U.M. outputs (total for all machines)
L --- maximum number of U.M. 6-character names (total for all machines)

All machine data is grouped together, and should follow the la conventional (non-dynamic) EMTP source card, just as is the case with the existing production S.M. modeling. The beginning of U.M. dat is signaled by two data cards:

Card 1 : Punch "19" in columns 1-2, as a special request for U.M. modeling. The rest of the card is left blank.

Card 2 : Punch column 1 with a flag which indicates whether or not data is to be in per unit:

1 ⟹ input data is in per unit.
0 ⟹ input data is in physical units (ohms, volts, amperes, henries). A blank produces the sam effect as an explicitely-punched zero.

There is nothing else on this second card (leave columns two through 80 blank).

B. Data Cards for Machine Table of U.M.

Next (after Card 2 of Section A) come all data cards for Hian's Machine Table, three cards for each U.M. component (for each induction machine, in this case). There is a blank terminator marking the end of all of these cards. E.g., if there are two induction machines, Class B data consists of 6 Machine Table cards, plus the blank terminator. Call these three cards Card A, Card B, and Card C, respectively. Format requirements are:

Card A : JTYPE ---- Columns 1-2, format I2 . Type code. Punch with "4" for 3-phase induction machine with 3-phase rotor.

JTQOUT ---- Column 7, format I1 . Flag for the request of output of the electromechanical torque TQGEN . Punch with "1" for such output; leave blank or punch with zero to suppress it.

JOMOUT ---- Column 8, format I1 . Like JTQOUT , only for the mechanical speed ω_m in radians/second .

JTHOUT ---- Column 9, format I1 . Like JTQOUT , only for the mechanical angle θ_m in radians .

SHAFT ---- Columns 10-15, format A6 . Name of the electric network node which represents the rotor mass (remember the use of electrical analog).

NPPAIR ---- Columns 22-23, format I2 . Number of pole pairs of the machine (e.g., "2" for 1800 rpm at 60 Hz with zero slip).

Card B : $\omega_m(0)$ ---- Columns 1-14, format E14.5 . The initial mechanical speed (at time zero), in radians/sec.

L^U_{md} ---- Columns 15-28, format E14.5 . The unsaturated value for the main (i.e., non-leakage) d-axis inductance, in units of Henries .

Card C : $\theta_m(0)$ ---- Columns 1-14, format E14.5 . The initial mechanical angle (at time zero), in radians .

L^U_{mq} ---- Columns 15-28, format E14.5 . The unsaturated value for the main (i.e., non-leakage) q-axis inductance, in units of Henries .

C. Data Cards for Coil Table of U.M.

After the Machine Table data of Section B, the user must supply data cards for the Coil Table of the U.M.. For the 3-phase induction machine being considered, there are six such cards for each machine. If more than one machine, ordering of these groups of six cards must correspond to the machine ordering of Section B. There is a blank terminator card after the last such set of six data cards for th final machine. Of the six data cards, the first three are for the power circuit (armature of the conventional induction machine), and th final three are for the excitation circuit (rotor of conventional induction machine). The symbolic parameter content is (see next page)

Card 1:	R_o	L_o	i_a	Power side, in (a, b, c) order, note.
Card 2:	R_d	$L_{d\ell}$	i_b	
Card 3:	R_q	$L_{q\ell}$	i_c	
Card 4:	R_d	$L_{d\ell}$	i_b	Excitation side, in (b, c, a) order, note.
Card 5:	R_q	$L_{q\ell}$	i_c	
Card 6:	R_o	L_o	i_a	

This shows the order of the cards, and the symbolic association of the three floating-point parameters on each data card; it does not show the data format of a typical card, however, which is as follows:

R, L ------- Columns 1-28, format 2E14.5 .

BUS1, BUS2 ------- Columns 29-40, format 2A6 . These are the EMTP node names for the terminal connections of the coil. Two blank names imply a shorted coil (both ends connected to ground). For an open circuit, leave one name blank and punch the other with the name of a dummy EMTP node that has a high impedance connected to ground.

TACS ------- Columns 41-46, format A6 . This is the name of a TACS variable whose value is to give the value of a voltage source connected to the coil (see sketch)

JCLOUT ------- Column 47, format I1 . This is a request flag for output of the coil current (see sketch as to the sign convention). Leave blank for no such output; punch "1" in column 47 to produce it.

CUR ------- Columns 48-61, format E14.5 . This is the initial current (value at time zero) in amperes .

The blank card which terminates this Coil Table data is also the last U.M. data card. Then comes the blank card ending EMTP sources, and the rest of the data case is quite conventional.

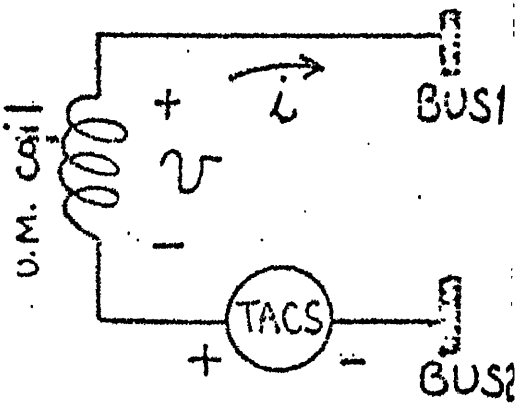


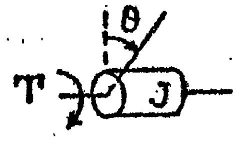
Fig. 1. Signs of coil current and voltages.

D. Modeling of the Shaft System

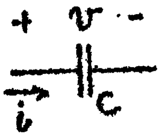
The masses and springs that are built into the production S.M. model are explicitely represented in U.M. modeling by an electrical analog. For each rotor mass, there is a capacitor to ground; for each spring interconnecting rotor masses, there is an inductor between the capacitor nodes. Applied (load) torque becomes injected current into such a capacitor node. Etc. as per the following correspondence:

Mechanical quantity	Electrical quantity
T (torque on mass)	i (current into node)
ω_m (angular speed)	v (node voltage)

θ_m	(angle)	q	(capacitor charge)
J	(moment of inertia)	C	(capacitance to ground)
K	(spring constant)	1/L	(reciprocal of inductance)
D	(viscous damping)	1/R	(conductance)



$$T = J\frac{d^2\theta}{dt^2} = J\frac{d\omega}{dt}$$

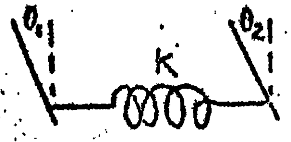


$$i = C\frac{dv}{dt}$$

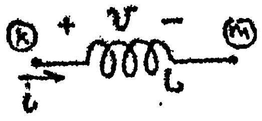
$T \sim i$ $\quad J \sim C$

$\omega \sim v$ $\quad K \sim 1/L$

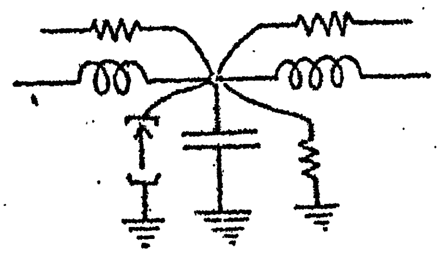
$\theta \sim q$ $\quad D \sim 1/R$

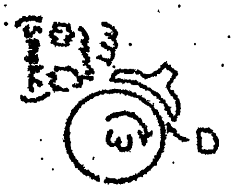


$$T = K(\theta_1 - \theta_2) = K\int^t(\omega_1-\omega_2)d\tau$$



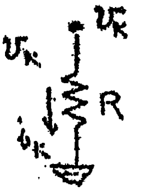
$$i = \frac{1}{L}\int^t (v_k - v_m)d\tau$$





$$T = D\omega$$

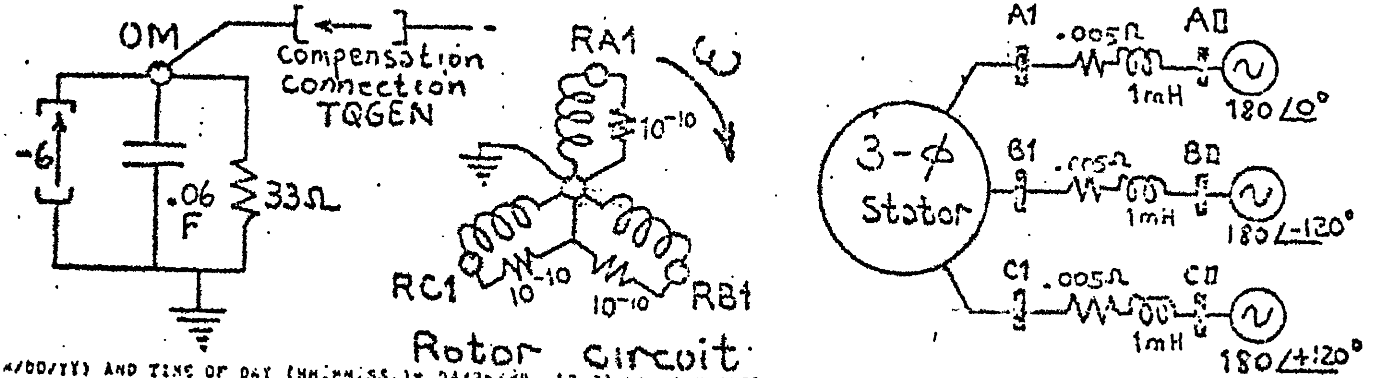
$$i_k = \left(\frac{1}{R}\right)v_k$$



Summarizing this in words, then, the user does the following. For each mass of the shaft system, he defines an electric network node with a capacitor of value J (the moment of inertia) to ground. If there is absolute-speed damping on this mass, he parallels the capacitor with a resistor having conductance D (the viscous damping constant). If there is an externally applied mechanical torque such as a mechanical load on this mass, he parallels the capacitor with a current source of value Tmech(t) (the time-dependent mechanical torque). The sign is such that a mechanical load becomes a negative injection. If there are two or more masses, one adds an inductor connecting the associated adjacent capacitors; value of the inductance is 1/K (reciprocal of the spring constant connecting the two masses). If there is speed-deviation damping associated with this coupling, the inductance is paralleled by a conductance of value DMUT (the viscous damping constant of this effect). There is no element representing the U.M. driving torque, since the EMTP provides this connection automatically. In terms of EMTP mathematics, the U.M. driving torque looks like a hidden nonlinear element which is connected from ground to the node of the capcitor that represents the rotor mass of the U.M. Hence do not expect the currents in branches that are connected to this node to sum to zero, for one branch is hidden. As for output of such mechanical variables, they are handled by column-80 requests on the branch cards representing the series R-L-C elements that are used. Remember that shaft torques are inductor currents, node voltages are mechanical s speeds, etc. If mechanical angles are wanted, one can pass the node voltages into TACS and integrate. Etc., etc.

(III) SAMPLE SIMULATION OF INDUCTION MOTOR STARTUP

Hian has set up a very nice little illustration of the induction machine mode of U.M. modeling. As can be confirmed by the EMTP data listing below, there is a 3-phase infinite bus (BUS-A0, BUS-B0, BUS-C0) which has "a"-phase at 180 volts, zero degrees, and 60 Hz. Series R-L branches with R = .005 and L = 1.E-3 henry connect this bus to the armature terminals (BUS-A1, BUS-B1, BUS-C1) For purposes of connectivity, the infinite bus is connected to ground by three resistors of value 1.0 ohm (the first three branch cards). Rotor windings are grounded-wye, with the ungrounded ends connected to the 3-phase electrical bus (BUSRA1, BUSRB1, BUSRC1) , which in turn is grounded by three resistors of value 1.E-10 ohm . Thus the rotor windings are effectively short-circuited. As for the mechanical side, node BUS-OM has capacitor C = .06 farad to ground representing the mass, and a parallel resistor R = 33,333 ohm to represent absolute viscous damping. The machine starts from zero speed, with all coil currents equal to zero. The Type-11 current source on node BUS-OM (value i = -6.0 amps) represents the mechanical load. Because there are two pole-pairs (NPPAIR = 2), synchrorous speed is 60 times Pi, or 188.4955 radians/sec.



```
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS.)= 04/25/80  12.23.51  ANY FLCTS BEAR SAME FIGURES.                   VERSION = "*27,* ,
IF IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE 564-PAGE EMTP USER'S MANUAL DATED NOVEMBER, 1977.
INDEPENDENT LIST LIMITS FOLLOW.  TOTAL LENGTH OF   /LABEL/  EQUALS 200123 INTEGER WORDS.     703  1050  2500    30  9500
  125  6100  5000     50   300   100   140  .  5  9000   400     9    4    30  6000   500    72   200  1000     6  3700
------------------------------------------------------+----------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA | INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER,
                                                  0         1         2         3         4         5         6         7
                                                  0         0         0         0         0         0         0         0
------------------------------------------------------+----------------------------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.              |BEGIN NEW DATA CASE
U.M. TABLE SIZES.     20     2    50   100        |ABSOLUTE U.M. DIMENSIONS, 20, 2, 50, 100
MISC. DATA.    0.200E-03   0.500E+00   0.000E+00  | .000200    .500
MISC. DATA.     1    1  0  0  1 -1  0  2  0  0    |       1        1        0       00        1       -1                2
PRINTOUT :      1    1    20    20   100   100    |       1        1       20       20      100      100
COMMENT CARD.                                     |C      FOLLOWING 3 BRANCHES ARE FOR CONNECTIVITY TO GROUND.
SERIES R-L-C.   0.100E+01  0.000E+00  0.000E+00  | 0      BUS-A0                 1.0
SERIES R-L-C.   0.100E+01  0.000E+00  0.000E+00  | 0      BUS-B0                 1.0
SERIES R-L-C.   0.100E+01  0.000E+00  0.000E+00  | 0      BUS-C0                 1.0
COMMENT CARD.                                     |C      NEXT COMES THE SOURCE IMPEDANCE (UNCOUPLED  R-L  BRANCHES).
SERIES R-L-C.   0.500E-02  0.100E+01  0.000E+00  | 0BUS-A1BUS-A0                  0.005 1.0
REFERENCE BRANCH.   COPY  'BUS-A1' TO 'BUS-A0'    | 0BUS-B1BUS-B0BUS-A1BUS-A0
REFERENCE BRANCH.   COPY  'BUS-A1' TO 'BUS-A0'    | 0BUS-C1BUS-C0BUS-A1BUS-A0
COMMENT CARD.                                     |C       NEXT SHORT CIRCUIT THE ROTOR WINDINGS WITH NEAR-ZERO RESISTANCE.
SERIES R-L-C.   0.100E-09  0.000E+00  0.000E+00  | 0BUSRA1                        1.E-10
SERIES R-L-C.   0.100E-09  0.000E+00  0.000E+00  | 0BUSRB1                        1.E-10
SERIES R-L-C.   0.100E-09  0.000E+00  0.000E+00  | 0BUSRC1                        1.E-10
COMMENT CARD.                                     |C      FINAL BRANCHES ARE FOR ROTOR MASS (CAPACITANCE) AND DAMPING (RESISTOR)
SERIES R-L-C.   0.000E+00  0.000E+00  0.600E+05  | 0BUS-OM                                       6.0E4
SERIES R-L-C.   0.333E+05  0.000E+00  0.000E+00  | 0      BUS-OM             33,333
BLANK CARD TERMINATING BRANCH CARDS.              |BLANK CARD ENDING BRANCHES
BLANK CARD TERMINATING SWITCH CARDS.              |BLANK CARD ENDING SWITCHES
SOURCE.     0.18E+03  0.60E+02  0.00E+00   0.00E+00 |14BUS-A0  180.0        60.0      0.0
SOURCE.     0.18E+03  0.60E+02 -0.12E+03   0.00E+00 |14BUS-B0  180.0        60.0     -120.0
SOURCE.     0.18E+03  0.60E+02  0.12E+03   0.00E+00 |14BUS-C0  180.0        60.0     +120.0
SOURCE.    -0.60E+01  0.00E+00  0.00E+00   0.00E+00 |11BUS-OM-1 -6.00
U.M. DATA BEGINS.  LIST-25 CELLS USED =  317       |19 UM
 BEGIN U.M.  INPU =   0                            |0
FIRST OF CARD SPLIT.      4     1     1            | 4 1 111BUS-OM        2 0.06                              0.18850
2ND OF SPLIT.   0.00000E+00   0.20291E-01     0    |0.0                0.020291       0
3RD OF SPLIT.   0.00000E+00   0.20291E-01     0    |0.0                0.020291       0
BLANK CARD ENDING MACHINE TABLE.                   |BLANK CARD ENDING UM MACH-TABLE
COIL   1.   0.63000E-01   0.19110E-03    1         |0.063              0.0001911     BUS-A1                1 0.0
COIL   2.   0.63000E-01   0.39250E-03    1         |0.063              0.0003925     BUS-B1                1 0.0
COIL   3.   0.63000E-01   0.39250E-03    1         |0.063              0.0003925     BUS-C1                1 0.0
COIL   4.   0.83000E-01   0.39250E-03    1         |0.083              0.0003925     BUSRB1                1 0.0
COIL   5.   0.83000E-01   0.39250E-03    1         |0.083              0.0003925     BUSRC1                1 0.0
COIL   6.   0.83000E-01   0.39250E-03    1         |0.083              0.0003925     BUSRA1                1 0.0
BLANK CARD ENDING COIL TABLE.                      |BLANK CARD ENDING UM COIL-TABLE
BLANK CARD TERMINATING SOURCE CARDS.               |BLANK CARD ENDING SOURCES
```

369-5

TPIM-7

Note that no EMTP phasor solution has been requested. Although not obvious to the reader, no user-specified initial conditions (after the blank card ending sources) were present, either. Hence the entire problem began with zero initial conditions. Well, on to the solution. EMTP printout of the time-step loop begins as follows:

```
STEP  TIME      BUS-A1        BUS-B1        BUS-C1        BUS-AG        BUS-OM        BUS-A1        BUS-B1        BUS-C1        TERRA
                                                                                    BUS-A0        BUS-B0        BUS-C0        BUS-OM

                UM-1          UM-1          UM-1          UM-1          UM-1          UM-1          UM-1          UM-1          UM-1
                TQGEN         OMEGM         THETAM        IPA           IPB           IPC           IE1           IE2           IE3
   0 0.000000 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
              0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
   1 0.000200 0.7921[illegible]E-02-0.344[illegible]E+02-0.448159E+02 0.179484E+01-0.999950E-02-0.100152E+03 0.435415E+02 0.566505E+02 0.779[illegible]E-03
             -0.3169[illegible]E-10-0.999950E-02 0.000000E+00-0.100142E+02 0.435437E+01 0.566225E+01 0.42[illegible]E+01 0.555257E+01-0.482[illegible]E+01
   2 0.000400 0.9011[illegible]E+02-0.2263[illegible]E+02-0.5953[illegible]E+02 0.1177[illegible]E+03-0.2997[illegible]E-01-0.77[illegible]E+02 0.25[illegible]E+02 0.41[illegible]E+02 0.[illegible]
             -0.36[illegible]E-03-0.[illegible]E+01-0.29[illegible]E-05-0.29[illegible]E+02 0.12[illegible]E+02 0.175[illegible]E+02 0.[illegible] 0.17[illegible]E+02-0.29[illegible]E+02
   3 0.000600 0.9[illegible]E+02-0.2[illegible]E+02-0.56[illegible]E+02 0.17[illegible]E+03-0.[illegible]E-01-0.[illegible]E+02 0.2[illegible]E+02 0.[illegible] 0.11[illegible]E+02
             -0.3[illegible]E-02-0.4[illegible]E-01-0.107[illegible]E-04-0.4[illegible]E+02 0.[illegible]E+02 0.30[illegible]E+02 0.[illegible]E+02 0.[illegible]E+02-0.4[illegible]E+02
   4 0.000800 0.[illegible]E+02-0.1[illegible]E+02-0.[illegible]E+02 0.17[illegible]E+03-0.[illegible]E-01-0.[illegible]E+02 0.20[illegible]E+02 0.[illegible]E+02 0.[illegible]E+02
             -0.1644[illegible]E-01-0.6[illegible]E-01-0.[illegible]E-04-0.675[illegible]E+02 0.23[illegible]E+02 0.[illegible]E+02 0.[illegible]E+02 0.[illegible]E+02-0.55[illegible]E+02
   5 0.001000 0.7[illegible]E+02-0.1[illegible]E+02-0.6[illegible]E+02 0.16[illegible]E+01-0.8[illegible]E-01-0.[illegible]E+02 0.12[illegible]E+02 0.[illegible]E+02 0.[illegible]E+02
             -0.45[illegible]E-01-0.[illegible]E-01-0.[illegible]E-04-0.8[illegible]E+02 0.2642[illegible]E+02 0.[illegible]E+02 0.2[illegible]E+02 0.[illegible]E+02-0.[illegible]E+02
   6 0.001200 0.[illegible]E+02-0.[illegible]E+01-0.[illegible]E+02 0.[illegible]E+03-0.1095[illegible]E+00-0.[illegible]E+02 0.4[illegible]E+01 0.[illegible]E+02 0.[illegible]E+02
             -0.1310[illegible]E+00-0.16[illegible]E+00-0.56[illegible]E-04-0.10[illegible]E+03 0.295040E+02 0.7179[illegible]E+02 0.279[illegible]E+02 0.[illegible]E+02-0.[illegible]E+03
```

To complete the display, I also show the final few steps, plus printout of the extrema. Note that since the preceding memo, we have added minima, and that maxima no longer involve the absolute value:

```
2300 0.460000-0.140618E+03-0.1[illegible]E+02 0.1554[illegible]E+03-0.145[illegible]E+03 0.197[illegible]E+01 0.5[illegible]E+01 0.393[illegible]E+01-0.[illegible]E+01-0.5625[illegible]E+01
              -0.1177[illegible]E+02 0.1[illegible]E+03 0.5[illegible]E+02 0.19[illegible]E+02-0.[illegible] 0.[illegible]E+01-0.[illegible] 0.[illegible]-0.[illegible]E+01
2400 0.480000 0.5310[illegible]E+02-0.15[illegible]E+03 0.1171[illegible]E+03 0.55[illegible]E+02 0.1[illegible]E+03-0.551[illegible]E+01 0.[illegible]E+01-0.[illegible]E+01-0.56[illegible]E+01
              -0.1[illegible]E+02 0.1[illegible]E+03 0.6[illegible]E+02 0.19[illegible]E+02 0.[illegible]E+01-0.[illegible]E+02-0.[illegible]E+01 0.[illegible]E+01-0.[illegible]E+01
2500 0.500000 0.171[illegible]E+03-0.[illegible]E+02-0.[illegible]E+02 0.[illegible]E+03 0.[illegible]E+01 0.[illegible]E+01 0.[illegible]E+01 0.[illegible]E+01
              -0.1145[illegible]E+02 0.[illegible]E+03 0.[illegible]E+02-0.[illegible]E+01 0.[illegible]E+02-0.150[illegible]E+02-0.[illegible]E+01 0.[illegible]E+01-0.[illegible]E+01

[illegible]IMA AND MINIMA WHICH OCCURRED DURING THE SIMULATION FOLLOW.   THE ORDER AND COLUMN POSITIONING ARE THE
[illegible] AS FOR THE REGULAR PRINTED OUTPUT VS. TIME.
VARIABLE MAXIMA :
                0.171728E+03 0.171769E+03 0.17184[illegible]E+03 0.1[illegible]E+03 0.17[illegible]E+03 0.99677[illegible]E+02 0.[illegible] 0.[illegible]E+03 0.743949E-02
                0.1[illegible]E+03 0.1[illegible]E+03 0.6529[illegible]E+02 0.[illegible]E+03 0.2[illegible]E+03 0.37[illegible]E+03 0.[illegible]E+03 0.[illegible]E+03 0.[illegible]E+03
TIMES OF MAXIMA :
                0.366000E+00 0.3[illegible]E+00 0.3[illegible]E+00 0.500000E-01 0.2[illegible] 0.910000E-01 0.[illegible]E-01 0.35[illegible]E-01 0.[illegible]E-02
                0.380000E-01 0.2[illegible]E+00 0.5[illegible]E+00 0.128[illegible]E+00 0.15[illegible]E+00 0.620[illegible]E-02 0.[illegible]E-01 0.600000E-02 0.1[illegible]E+00
VARIABLE MINIMA :
               -0.17187[illegible]E+03-0.1[illegible]E+03-0.17[illegible]E+03-0.1[illegible]E+03-0.24[illegible]E+0[illegible]-0.1[illegible]E+03-0.[illegible]E+02-0.1[illegible]E+03-0.5[illegible]E+01
               -0.1[illegible]E+03-0.2[illegible]E+00-0.7[illegible]E+03-0.1[illegible]E+03-0.3[illegible]E+03-0.2[illegible]E+03-0.3[illegible]E+03-0.[illegible]E+03-0.[illegible]E+03
TIMES OF MINIMA :
                0.356400E+00 0.3[illegible]E+00 0.3[illegible]E+00 0.2[illegible]E-01 0.320000E-02 0.1[illegible]E-01 0.71[illegible]E-01 0.1[illegible]E-01 0.2[illegible]E+00
                0.11[illegible]E-01 0.[illegible]E-02 0.500000E-02 0.370000E-01 0.680000E-02 0.147800E+00 0.[illegible]E-02 0.[illegible]E-01 0.40[illegible]E-01
```

Now on to the plotting, to really see what is happening. Plots are shown on the following page. We have:

Fig. 1 : Plot of "a"-phase rotor current over the full half second of simulation time. This starts off as 60 Hz ac, but after about 0.4 seconds it looks like dc (the machine is up to speed, with slip so small that the sinusoidal curvature is not obvious over the observation time of the plot).

Fig. 2 : Like Fig. 1, only just for the first 50 msec of the simulation. The 60 Hz sinusoidal character is obvious.

Fig. 3 : Plot of rotor speed (UM-1, OMEGM) over the full half second of simulation. Note the 60 Hz oscillation over the first 120 msec or so. Why does it die out when it does, Hian? What governs the amplitude of this? At about 240 msec, the rotor slightly overshoots its final speed, and thereafter there is a rapidly damped decay to the final operating point.

Fig. 4 : Plot of electromechanical torque (UM-1, TQGEN) over the full half second of simulation. This begins with a 60 Hz oscillatory component (see Fig. 5), and ends as a constant. The time range (.25, .40) is readily understood to produce a balancing torque about the steady-state operating point.

36g-6

TPIM-8

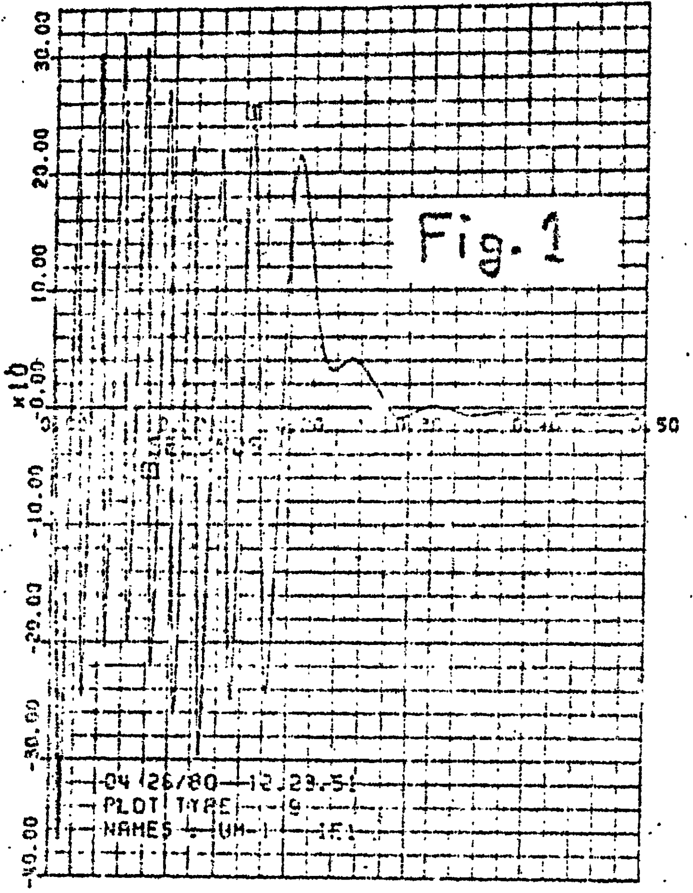


Fig. 1

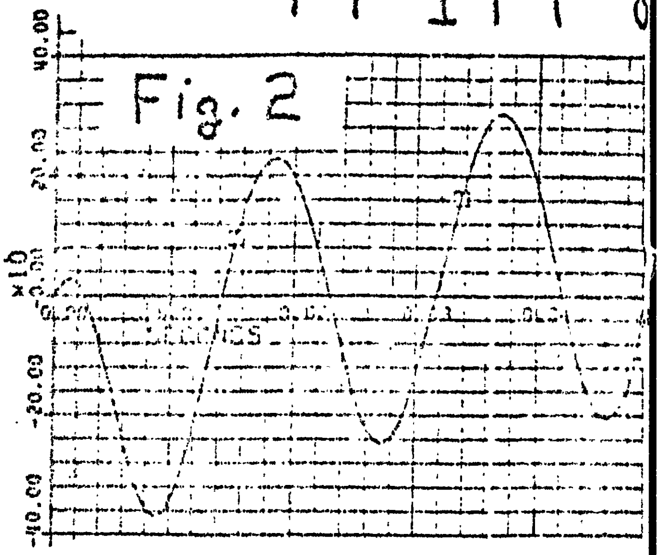


Fig. 2

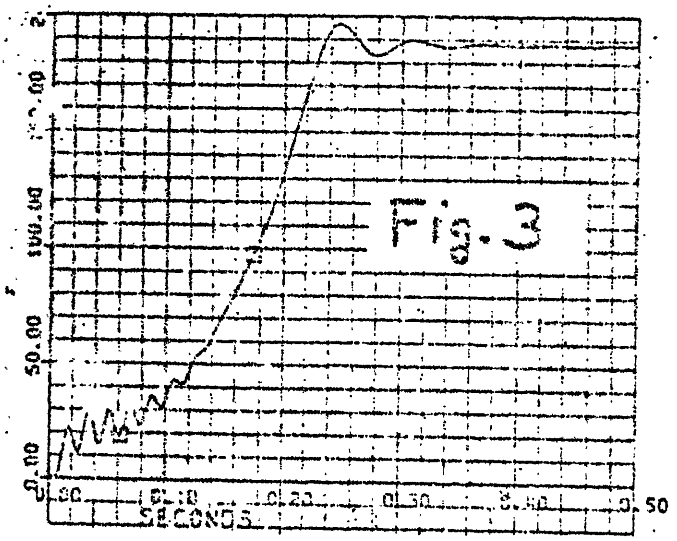


Fig. 3

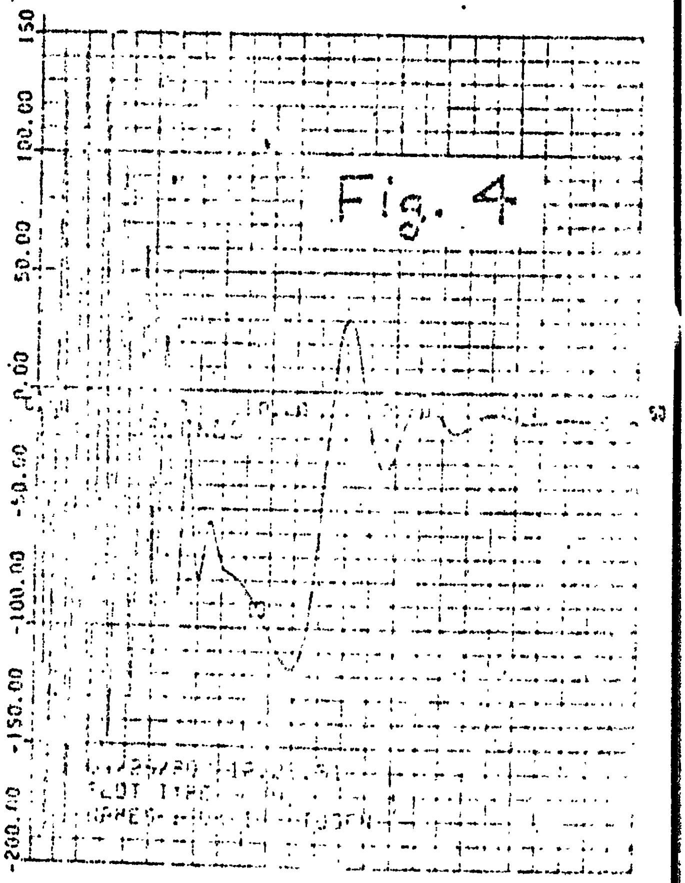


Fig. 4

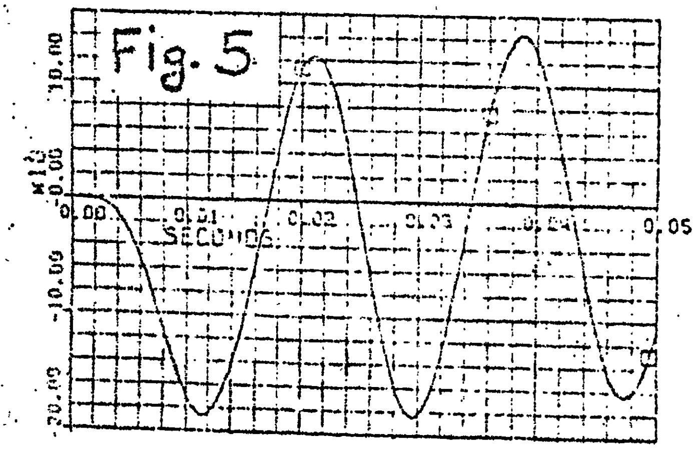


Fig. 5

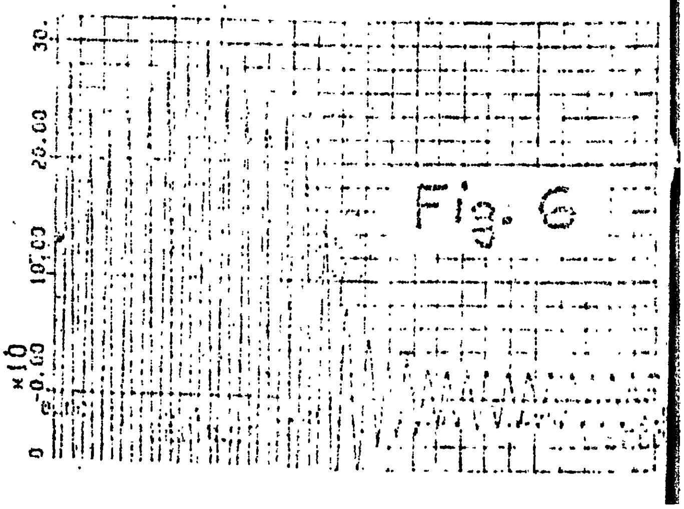


Fig. 6

36g-7

385

TPIM-9

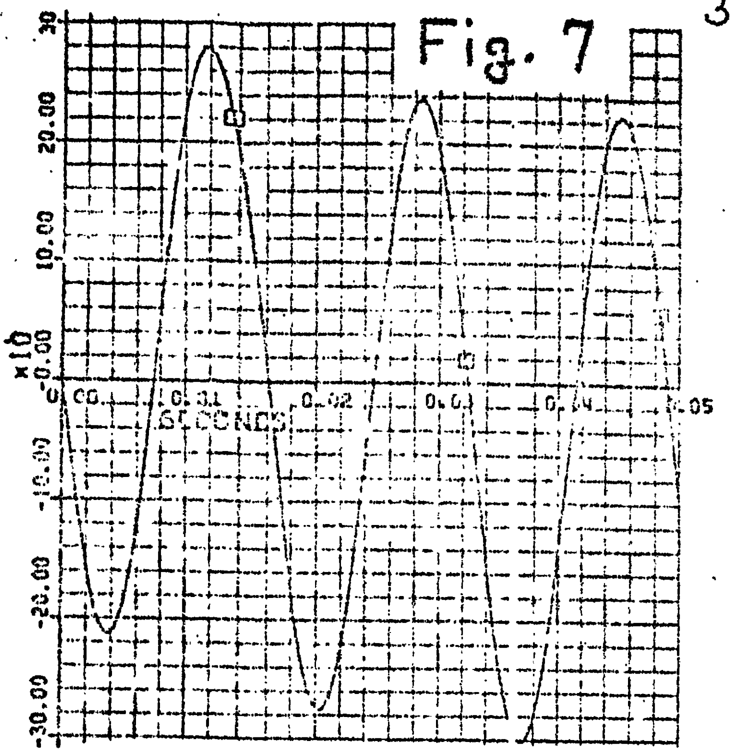
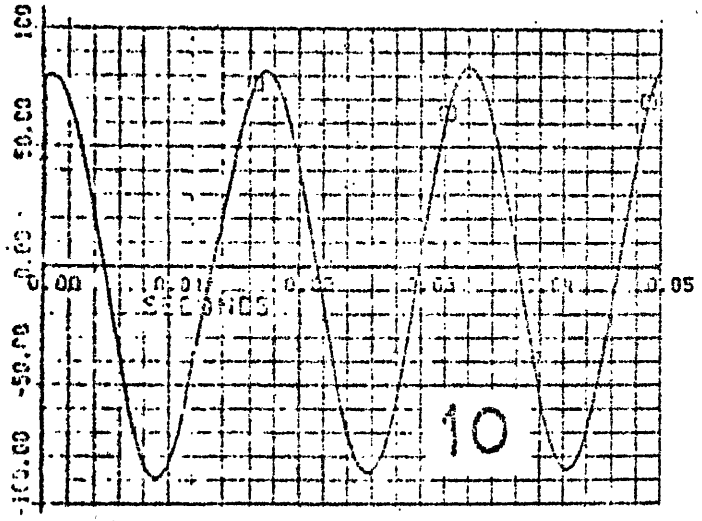
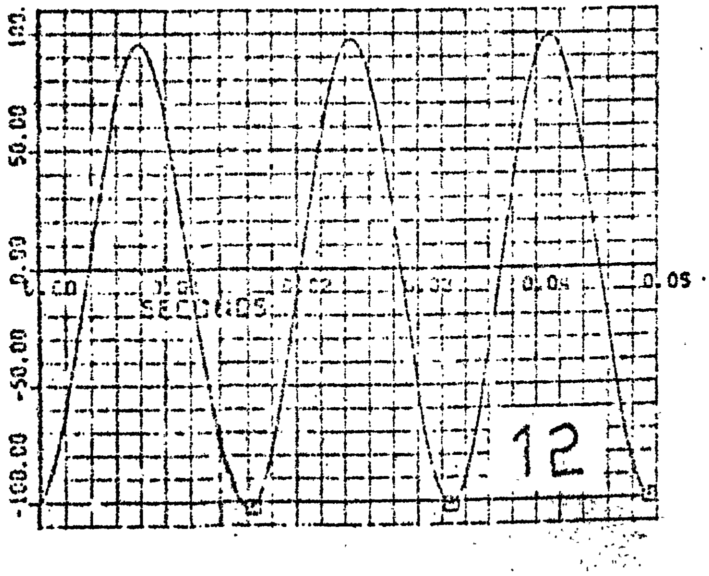
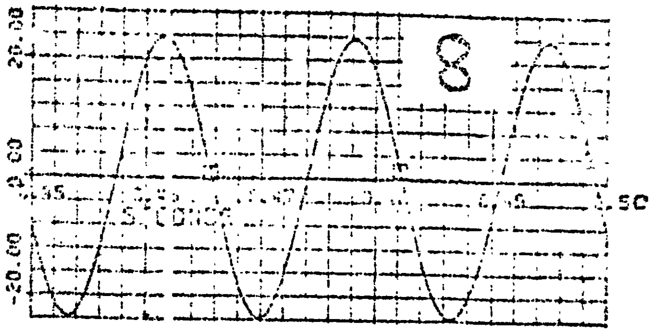


Fig. 7


10


12


8

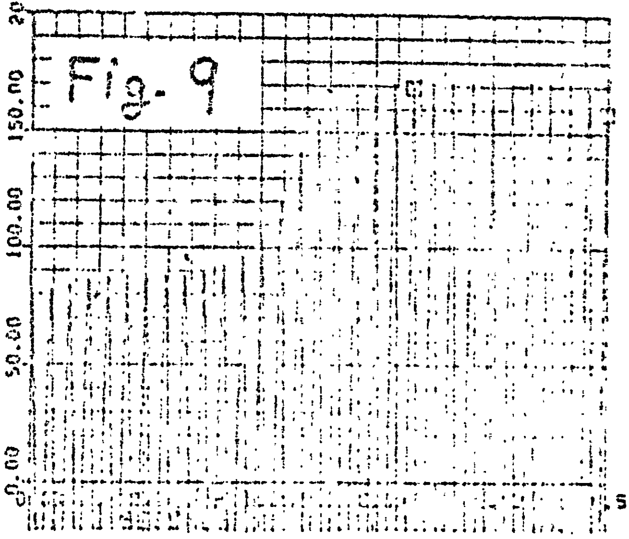


Fig. 9

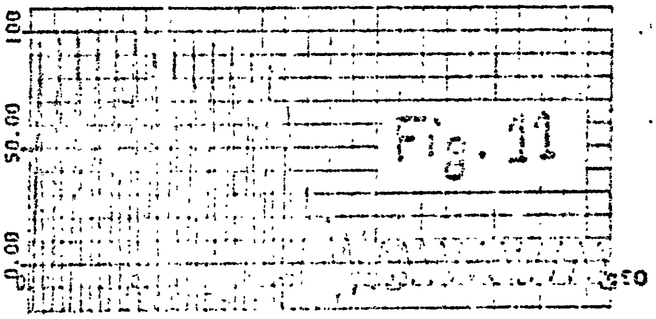


Fig. 11

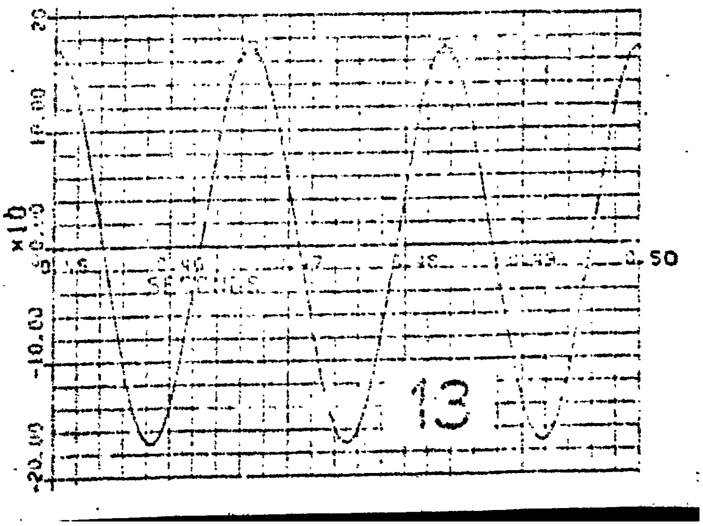

13

Fig. 5 : Like Fig. 4, only just for the first 50 msec of the simulation. The 60 Hz sinusoidal character with small negative offset is obvious.

Fig. 6 : Armature current (UM-1, IPA) over the full half second of simulation time. This is basically a 60 Hz sinusoidal signal, though strongly amplitude modulated. The initial modulation, over the first 150 msec or so, seems to have a period of about 100 msec (why, Hian?). After about 300 msec , the final steady state is reached, with armature current peaks of about 24 amps .

Fig. 7 : Like Fig. 6, only just for the first 50 msec of the simulation. The 60 Hz sinusoidal shape is obvious.

Fig. 8 : Like Fig. 6, only for the final 50 msec of the simulation. The symmetric, 60 Hz sinusoidal character is obvious.

Fig. 9 : Phase "a" armature voltage "BUS-A1" over the full half second of simulation. This is basically a 60 Hz sinusoidal signal, though strongly amplitude modulated. The rapid change in the envelope occurs over the time range (180, 280) msec , for reasons which maybe Hian can explain.

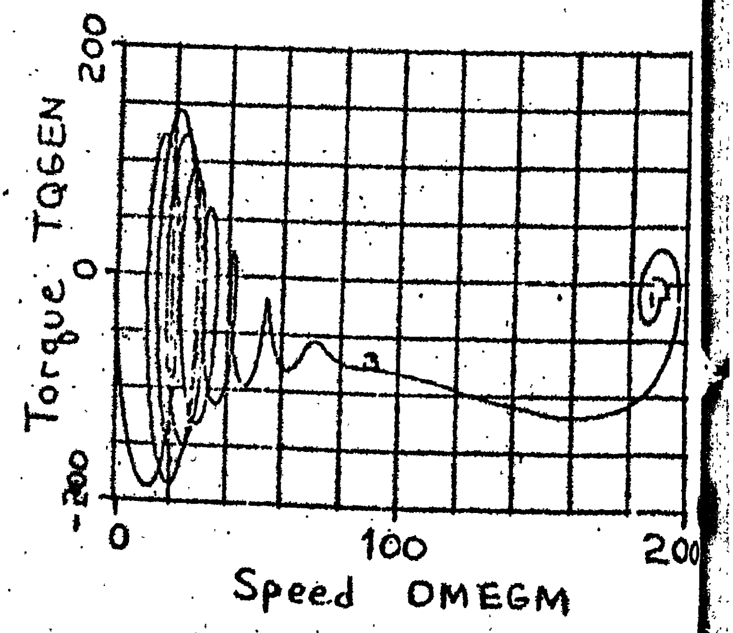
Fig. 10: Like Fig. 9, only just for the first 50 msec of the simulation. Note the sinusoidal 60 Hz character.

Fig. 11: Phase "a" voltage drop across the R-L source impedance/ EMTP branch voltage (BUS-A1, BUS-A0) . This is amplitude-modulated 60 Hz signal. The envelope change correlates with that of Fig. 9, of course, by Kirchhoff's voltage law.

Fig. 12: Like Fig. 11, only for the first 50 msec of the simulation. The sinusoidal nature, with slight initial offset, is obvious.

Fig. 13: Like Fig. 11, only for the final 50 msec of the simulation. The balanced 60 Hz sinusoidal nature is obvious.

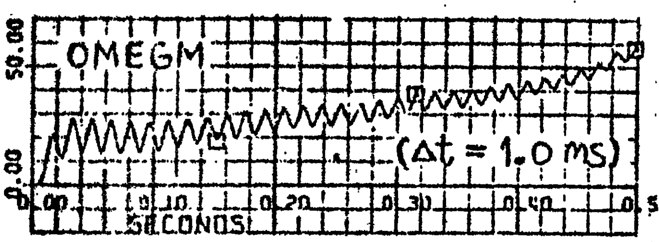
So much for conventional plots as functions of time. Hian says that one more plot would be most valuable: torque (UM-1, TQGEN) as a function of speed (UM-1, OMEGM). Hian says that such a curve is very meaningful to designers. Could be, though I myself would not know what to do with it! The locus started on the left (zero speed), and moved to end up in a fine spiral on the right, as the oscillation about the loaded operating point died out. But what about that region from zero to 80 rad/sec , where it looks like someone trying to start a jammed ball point pen?! Note that this looks nothing like the classic single-valued steady-state curve. We will get Hian to add some words of wisdom at the end. After all, he was the one who ordered it!

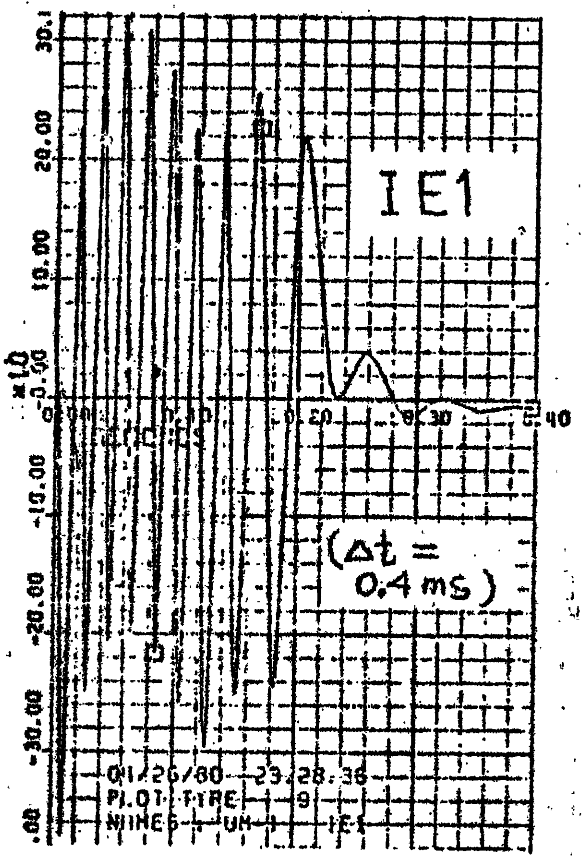


TPIM-11

I do not have many more comments about this example. The time-step size of 0.2 msec was selected arbitrarily. It seems to be sufficiently small, since a rerun using 1000 steps of size 0.1 msec produced Versatek plots which superimpose perfectly with those just shown (plotted to the same scale, one holds them up to the light). As for larger steps, I can assure the reader that 1.0 msec is too big. Shown at the right is the speed (UM-1, OMEGM) --- not much of a likeness to Fig. 3. As for intermediate steps, 0.4 msec seems to give good results. Plots of "OMEGM", "IPA", and "TOGEN" superimpose perfectly with Figures 3, 6, and 4, respectively, over the 400 msec of the simulation. But rotor current "IE1" showed a minor difference, just around that relative minimum at time 220 msec (compare the result at the right with Fig. 1). One might be able to run with time step equal to half a millisecond, then, if one is not too particular about minor details. But this is about the limit.

So much for WSM's work on this problem. As with the preceding memo, I encourage Hian to comment on whatever aspects occur to him, in the rest of this section. Hian!



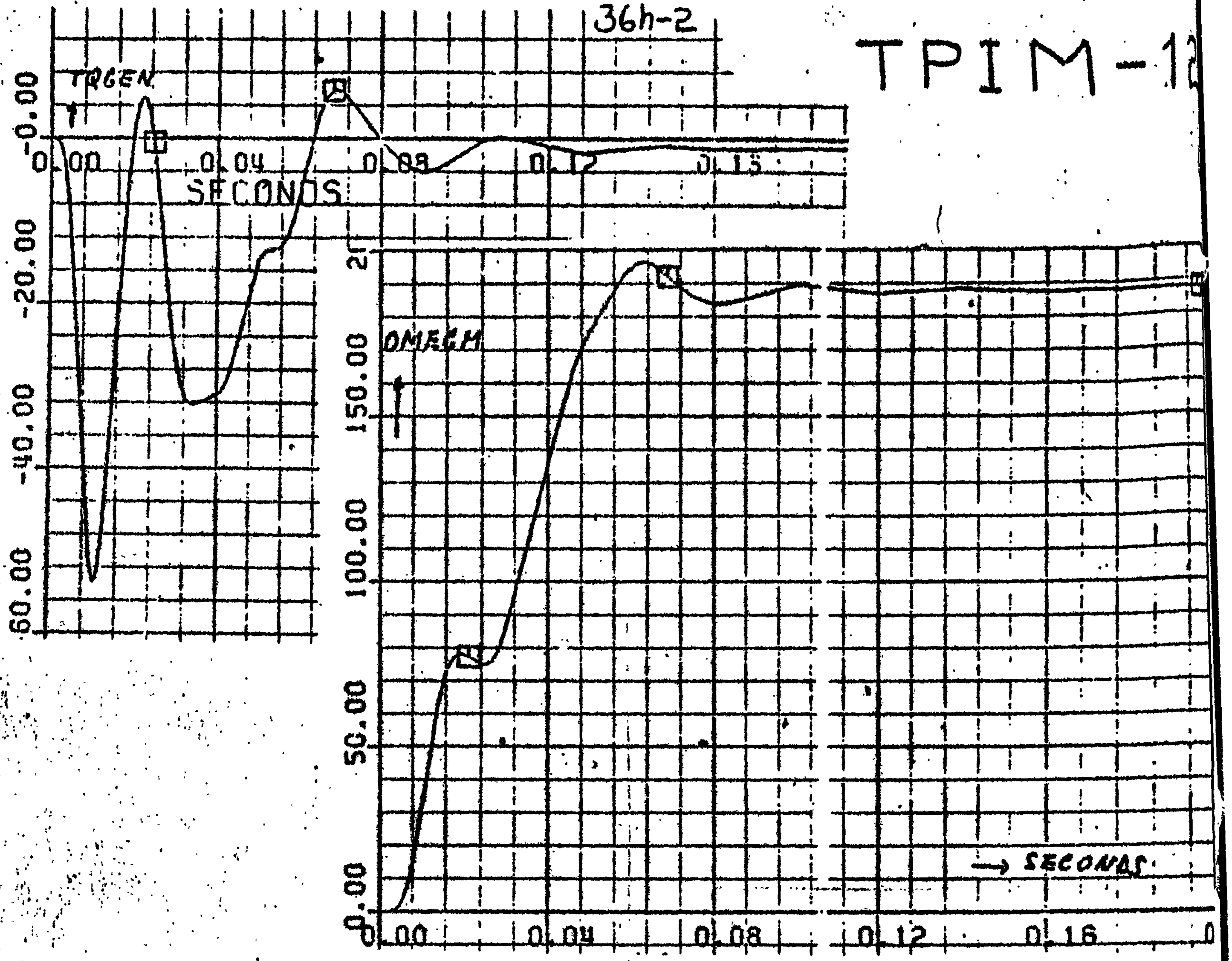


Note on Scott's Memorandum, d.d. April 15, 1980

First of all, I'd like to express my appreciation to Scott for the clear documentation of his experience with this first use of the induction machine mode of the U.M. The machine with a rating of 30 hp, 220V, four pole, 60 Hz, y-connected, was subjected to an energization test, which gives rise to one of the most severe transient conditions for an induction motor.

It is very reassuring to know that the U.M. transient torque-speed characteristics matches exactly with the results as published by NASAR and UNNEWEHR in their book: "Electromechanics and Electric Machines," John Wiley and Sons, 1979, pp. 422-425. It has to be noted that the U.M. torque-speed characteristics are upside down as compared with conventional usage. This is because the sign convention of the U.M. variables are generator based, thus, if the U.M. is in motor mode, then the electromechanical torque is negative. It is also to be pointed out that the shown U.M. torque-time characteristic at Fig. 4 has much more pronounced oscillations than the one shown by NASAR and UNNEWEHR, due to their zero line reactance. Scott also did run this case, which then shows an exact match. The corresponding U.M. output is given in the figure below (see next page):

TPIM-1

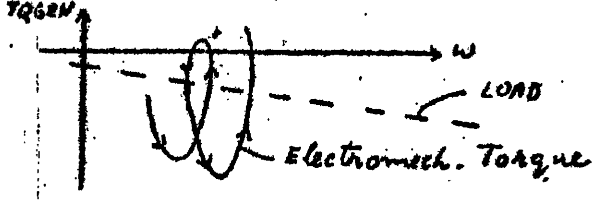


Now my comments as invited by Scott on the following items.

(a) The reason for the rotor speed oscillation to die out after about 120 msec, as shown in Fig. 3. This is due to the fact that thes oscillations are "governed" by the oscillations of the electromechanical torque TQGEN. As evidenced by the output of Fig. 4, the severe oscillations in this torque indeed subside after about 120 msec. The behavior of the electromechanical torque during energization is difficult to predict, it really forms the motivation for having an appropriate transient model to reveal the interesting transient world of induction machines. Simplified linearized analysis produces nonvalid results, particularly due to the strong nonlinear coupling of mechanical speed and electric currents during the energization process (induction motors have relatively small rotor moments of inertia). For example, it is known that the oscillatory behavior of the electromechanical torque as shown in Fig. 4 is dependent on the time interval between closing of the switches on the three lines. Another important effect to this oscillatory behavior is the machine leakage inductance, as well as the line reactances.

(b) Modulation of armature current, as shown in Fig. 6. Scott observed a low frequency modulation with a period of about 100 msec. The observed periodicity is deceiving, Scott, due to the fact that the modulation is generated by the behavior of the product of rotor speed and main flux. A simplified linearized analysis predicts a decay of the envelopes of the armature currents, if it is assumed that the rotor speed is increasing as a ramp function. However, as can be seen from Fig. 3, this assumption is not very valid during the first 100 msec. The average rate of increase of the rotor speed at a certain interval in this period is lower than in the other periods. My own experience is that the referred-to modulation can be more or less suppressed by decreasing the leakage inductance or by decreasing the line reactance.

(c) Significance of the transient torque-speed curve. The transient torque-speed characteristics are significant in the sense of providing an understanding to the transient behavior relative to the rather well predictable steady-state torque-speed curve. The importance of this understanding is shown in numerous studies, for example: the study of oscillatory torque behavior near zero slip due to stator resistance effect, torque production during fault recovery and of course, during energization. Although not apparent from the figure on page TPIM-1C, the transient torque-speed is regular. It has to be realized that if in motor operation the electromechanical torque is greater than the load torque, then the rotor speed is increasing. And vice versa, if this torque is smaller than the load torque, then the rotor speed is retarded. Hence for one oscillation, the following behavior of the transient torque-speed curve will be seen (note: for motor operation the electromechanical torque = - TQGEN because of the U.M. generator convention):



1.63B Complete Rules for U.M. Data Assembly and Usage

The U.M. module of the EMTP currently can be used to represent 12 major types of electric machines, as will be described in the next section. Despite the universality of the program set-up, a serious attempt is made not to burden the user with this universality if only the use of one or a few of the available types is desired. Therefore in the next section, Section 16.3b, a user's guide is given for each U.M. type. Then taking up these instructions for the desired U.M. type, reference will be found to the rules for setting up the three classes of U.M. data cards as described in Sections 16.3c, 16.3d and 16.3 . Finally in Section 16.3f the meaning for the labels of the output is explained.

In this introduction, the following points can be remarked:

(a) Number of machines and coils, compensation:

The number of U.M. machines which can be used is arbitrary. For each machine the following rules apply. The maximum number of coils on the power side is restricted to three. This is obviously justified by our today's usage of electric machines. These three coils are 3-phase compensated, i.e., they can be externally connected to each other in one electrical network. As far as compensation of the excitation coils is concerned, the general rule here is that only the first three excitation coils are 3-phase compensated, i.e., only the first three excitation coils are permitted to be externally connected to each other in one single electric network. If in addition more excitation coils are used, then each of these coils must be totally disconnected from other coils used. It is to be remarked that the above outlined restrictions can be overcome by the approach of using stub lines or inserting a TACS element between U.M. machines or between coils which are not supposed to be connected with each other.

(b) Saturation:

User has the option of implementing a d-axis, a q-axis or both d- and q-axis saturation non-linearity. The actual saturation curve is to be approximated by a two straight-line segment curve at this moment of writing.

(c) Use of network representation of mechanical system:

Users of the U.M. module have the option to employ the network representation of the mechanical system. This network representation can then b handled by the Electrical Network section of the EMTP. This approach provides the means to use the efficient sparsity oriented solution method of the EMTP, in addition to its variable dimensioning feature. Moreover, no time-step delay is required in interfacing the U.M. module with the mechanical system In determining the network representation of the mechanical system, the following correspondence of the parameters have to be considered:

* Moment of inertia of mass = capacitance
* Spring coefficient = 1/inductance
* Damping coefficient = 1/resistance
* Torque = current
* Speed = voltage

(d) Initialization:

Automatic initialization is not available yet. Until this feature is implemented, the U.M. requires initialization of all coil currents, whereas coil terminal voltages have to be initialized by the Electrical Network Section of the EMTP. For the mechanical side, the initialization of the mechanical speed and rotor position angle (or torque angle for synchronous machines) is needed.

16.3b User's Guide

This section contains the steps of action to be undertaken by the user to set up the data case for any of the 12 available U.M. types:

Type 1 = synchronous machine, 3-phase power side
Type 2 = synchronous machine, 2-phase power side
Type 3 = induction machine, 3-phase power side
Type 4 = induction machine, 3-phase power side and 3-phas excitation side
Type 5 = induction machine, 2-phase power side
Type 6 = single-phase a.c. machine, induction or synchronous, 1-phase excitation
Type 7 = same as type 6 but 2-phase excitation
Type 8 = d.c. machine; separately excited
Type 9 = d.c. machine, series compound (long shunt)
Type 10 = d.c. machine, series
Type 11 = d.c. machine, parallel compound (short shunt)
Type 12 = d.c. machine, parallel

Note: Except for Type 4, 6 and 7, all machine types can have an arbitr ry number of d- and q- axis excitation coils. The 3-phase excitation axis of Type 4 are 120 degrees shifted.

U.M. Type 1 User's Guide

U.M. Type 1 = synchronous machine, 3-phase power side, arbitrary number of excitation coils in d- and q-axis.

Step (1): Set up the general specification data cards according to the instructions of Class 1 U.M. Data Cards (Section 16.3c)

Step (2): Set up the machine-table data cards according to the instructions of Class 2 U.M. Data Cards (Section 16.3d)

Step (3): Set up the coil-table data cards according to the instructions of Class 3 U.M. Data Cards (Section 16.3e)
Exception to these instructions is with regard to the specification of the resistances and leakage inductances in the coil cards representing the power coils:

(a) Resistances of the power coils A, B and C are required to be equal to each other. If the case of non-equal resistances is desired to be studied, then the following valid strategy has to be followed. Insert to the U.M. equal resistances with values equal to the smallest resistance. Then account for the remaining resistances of the coils by connecting in the Electrical Network resistance branches in series to the U.M. coil. This is also a valid approach for studies of frequency dependency of the resistances.

(b) Specify for the leakage inductances LLEAK on the coil cards according to the rule:

on coil card A: LLEAK = total inductances of zero component

on coil card B: LLEAK = d-axis leakage inductance

on coil card C: LLEAK = q-axis leakage inductance

REMARK: These inductances can be found from the self- and mutual-inductances by applying a similarity transformation with the Park transformation matrix. See for example Fouad and Anderson, "Power System Control and Stability," Iowa State University Press, 1977, pp. 85-98.

U.M. Type 2 User's Guide

U.M. Type 2 = synchronous machine, 2-phase power side, arbitrary number of excitation coils in d- and q-axis.

Step (1): Set up the general specification data cards according to the instructions of Class 1 U.M. Data Cards (Section 16.3c)

Step (2): Set up the machine-table data cards according to the instructions of Class 2 U.M. Data Cards (Section 16.3d)

Step (3): Set up the coil-table data cards according to the instructions of Class 3 U.M. Data Cards (Section 16.3e).
Exception to these instructions is with regard to the coil cards representing the power coils:

(a) The two-phase power coils have to be chosen as power coil B and C. Since power coil A is not used, the coil card representing power coil A is to be completely left blank.

(b) Resistances and leakage inductances which have to be specified in the coil cards representing the power coils B and C, must follow the same instructions as outlined in Step (3) of U.M. Type 1 (except of course that reference to coil card of power coil A has to be disregarded).

U.M. Type 3 User's Guide

U.M. Type 3 = induction machine, 3-phase power side, arbitrary number of excitation coils in d- and q-axis.

Step (1): Set up the general specification data cards according to the instructions of Class 1 U.M. Data Cards (Section 16.3c)

Step (2): Set up the machine-table data cards according to the instructions of Class 2 U.M. Data Cards (Section 16.3d)

Step (3): Set up the coil-table data cards according to the instructions of Class 3 U.M. Data Cards (Section 16.3e).
Exception to these instructions is with regard to the specification of the resistances RESIS and the leakage inductances in the coil cards representing the power coils. The instruction to be followed is outlined in Step (3) of U.M. Type 1.

U.M. Type 4 User's Guide

U.M. Type 4 = induction machine, three-phase power side and three-phase excitation side.

Step (1): Set up the general specification data cards according to the instructions of Class 1 U.M. Data Cards (Section 16.3c)

Step (2): Set up the machine-table data cards according to the instructions of Class 2 U.M. Data Cards (Section 16.3d).
Exception to these instructions is with regard to the specification of NCLD and NCLQ for card (1), which both have to be left blank.

Step (3): Set up the coil-table data cards according to the instructions of Class 3 U.M. Data Cards (Section 16.3e), where rule numbers (3.2) and (3.3) have to be disregarded. Then additionally the following rules apply:

(a) Instead of the mentioned rules (3.2) and (3.3) pertaining to the arrangement of the excitation coil cards, the rule here is that the power coil cards have to be followed with excitation coil cards in the sequence of coil B, coil C and coil A. Note that the power coil cards are supposed to be arranged in the sequence of coil A, coil B and coil C according to rule number (3.1) of Class 3 U.M. data cards.

(b) Specify the resistances RESIS and the leakage inductances LLEAK on the coil cards representing the power coils A, B, C according to the same rules as outlined for Step (3) of U.M. Type 1.

(c) Same as (b) for the coil cards representing the excitation coils A, B and C.

U.M. Type 5 User's Guide

U.M. Type 5 = induction machine, 2-phase power side, arbitrary number of excitation coils.

Set up the data case for this type according to the same instructions as outlined for U.M. Type 2.

U.M. Type 6 User's Guide

U.M. Type 6 = single-phase A.C. machine, induction or synchronous, 1-phase excitation.

Step (1): Set up the general specification data cards according to the instructions of Class 1 U.M. Data Cards (Section 16.3c)

Step (2): Set up the machine-table data cards according to the instructions of Class 2 U.M. Data Cards (Section 16.3d). Exception to these instructions is with regard to card (1) variables NCLD and NCLQ. Due to the internal U.M. coil arrangement, these variables have to be specified as:

NCLD = 1, NCLQ = leave blank or 1 if an auxiliary starting coil is desired.

Step (3): Set up th coil table data cards according to the instructions of Class 3 U.M. data cards (Section 16.3e), but completely disregard rule number (3) about the sequence of coil cards belonging to one machine. Instead the following rules have to be followed:

(a) First insert 2 blank cards.

(b) Then comes the coil card representing the excitation coil. The current through this coil will be indicated in the output as IPC.

(c) Now comes the coil card representing the power coil. If NCLQ has been set equal to one, then this power coil card has to be followed with another coil card representing the auxiliary starting coil. The currents through the power coil and auxiliary coil will be indicated in the output as respectively IE_1 and IE_2.

U.M. Type 7 User's Guide

U.M. Type 7 = single-phase A.C. machine, induction or synchronous, 2-phase excitation.

The instructions to set up the data case are the same as for U.M. Type 6, except for rule (a) and (b) of Step (3), which now become:

(a) First insert 1 blank card.

(b) Then comes 2 coil cards representing the 2 excitation coils, which are spacially 90 degrees shifted from each other. The currents through these excitation coils will be indicated in the output as respectively IPB and IPC.

U.M. Type 8 User's Guide

U.M. Type 8 = d.c. machine, separately excited, arbitrary number of excitation coils in d- and q-axis.

Step (1): Set up the general specification data cards according to the instructions of Class 1 U.M. Data Cards (Section 16.3c)

Step (2): Set up the machine-table data cards according to the instructions of Class 2 U.M. Data Cards (Section 16.3d). In specifying NCLD and NCLQ on card (1) it is important to be aware of the fact that the power coil (armature coil) is on the q-axis. Thus usual wage of the machine is to arrange the excitation coils (field coils) on the d-axis.

Step (3): Set up the coil-table data cards according to the instructions of Class 3 U.M. Data Cards (Section 16.3e). Exception to these instructions is with regard to rule (3a), which instead must be replaced by the following rule:

* First insert 2 blank cards, and then follow with the coil card representing the power coil (armature coil), which is located on the q-axis.

U.M. Type 9, 10, 11, 12 User's Guide

U.M. Type 9 = d.c. machine, series compound (long shunt)
Type 10 = d.c. machine, series
Type 11 = d.c. machine, parallel compound (short shunt)
Type 12 = d.c. machine, parallel

Step (1): Set up the general specification data cards according to the instructions of Class 1 U.M. Data Cards (Section 16.3c)

Step (2): Set up the machine-table data cards according to the instructions of Class 2 U.M. Data Cards (Section 16.3d). Exception to these instructions is with regard to card (1) variables NCLD and NCLQ, which are to be specified as:

NCLQ = 2, NCLQ = leave blank.

REMARK: This means that the number of excitation (field) coils are fixed, namely 2 in the d-axis.

Step (3): Set up the coil-table data cards according to the instructions of Class 3 U.M. Data Cards (Section 16.3e), but completely disregard rule number (3) about the sequence of coil cards belonging to one machine. Instead the following rules have to be followed:

(a) First insert 2 blank cards

(b) Then comes the coil card representing the power (armature) coil. The U.M. considers this coil to be located on the q-axis.

(c) Finally comes 2 coil cards representing the 2 excitation (field) coils which by the U.M. is considered to be located on the d-axis. The first of these 2 coil cards specifies a shunt coil and the second a series coil. If no shunt coil or no series coil is used, then the corresponding coil card is to be left blank completely.

16.3c Class 1 U.M. Data Cards

This class contains two cards.

Card (1): indicates the request for the use of a U.M. model.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	9																																	
I	2																																	

Card (2): general specification

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
INPU																																		
I,																																		

INPU ---- Specifies the dimension of the physical quantities. If left blank, the SI units are to be used (V,A,W, sec, N.m, m, etc.). If 1 is punched, then the per unit system is to be used as described in: Fouad and Anderson: "Power System Control and Stability," Iowa State University Press, 1977, pp. 92-98, pp. 414-418.

16.3d Class 2 U.M. Data Cards (Machine-Table):

The Class 1 data cards have to be followed with this Class 2 of data cards, which specify general information about the U.M. models to be used (that is why this class of cards is called machine-table as opposed to coil-table which will form the Class 3 U.M. data cards).

General rule:

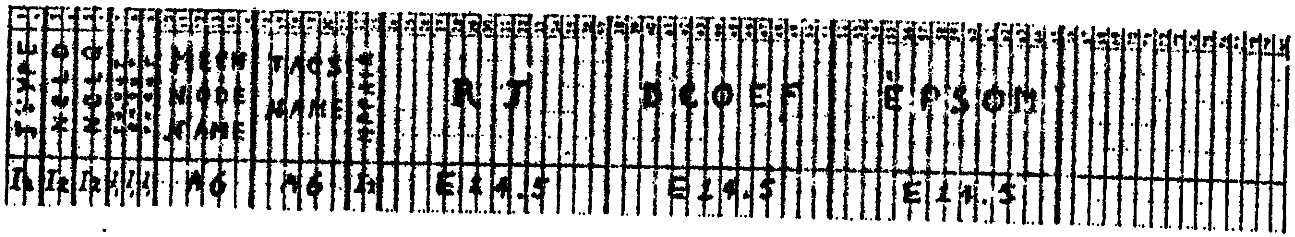
(1) Three cards are required for each machine. The first set of three cards will be considered by the program as to belong to a machine named UM-1, the second set of three cards belongs to UM-2, etc.

(2) A blank termination card is to be provided for ending this Class 2 U.M. data card.

Example: If 2 U.M. machines are to be used, then Class 2 U.M. data cards consist of 7 cards: first three cards for UM-1, second set of three cards for UM-2 and blank termination card.

The mentioned set of three cards as needed for each machine are:

Card (1) of Class 2 data cards:



J TYPE (1-2) ---- The U.M. type number desired to be used

NCLD (3-4) ---- Number of d-axis excitation coils.
Note: For J TYPE = 4, NCLD is to be left blank.

NCLQ (5-6) ---- Number of q-axis excitation coils.
Note: For J TYPE = 4, NCLQ is to be left blank.

TQOUT (7) ---- Request for output of electromechanical torque [N.m]
0 = no output, 1 = output requested.

OMOUT (8) ---- Request for output of rotor speed [rad/sec]
0 = no output, 1 = output requested

THOUT (9) ---- Request for output of angle indicating rotor position with respect to stator [rad]. For JTYPE = 1 and 2, this angle becomes the torque angle.
0 = no output, 1 = output requested.

Mech.Node Name (10-15) ---- Name of the node to which the U.M. mass (= capacitor) is connected if mechanical network option is used, i.e., mechanical shaft system is represented by its electrical network analog. If this network option is not used, then leave the assigned space blank.

TACS name ---- Name of the TACS variable, which forms the mechanical input
(16-21) torque to the U.M., if the mechanical system is not simulated by an electrical network representation.

Note: Leave this assigned space blank if the mechanical network option is used.

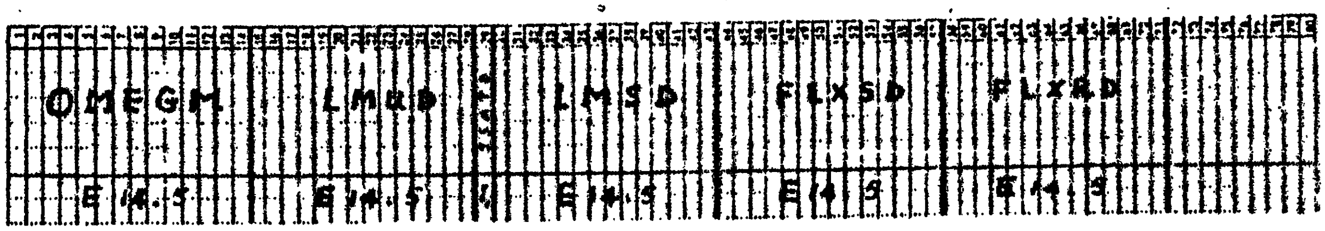
NPPAIR ---- Number of pole pairs.
(22-23)

RJ ---- Rotor moment of inertia in [N.m.sec^2/rad] or in per unit.
(24-37) Leave blank, if mechanical network option is used.

DCOEF ---- Dampings coefficient in [Nm sec/rad] or in [per unit]. Leav
(38-51) blank if mechanical network option is used.

EPSOM ---- Convergence margin for the rotor speed iteration process.
(52-65) If left blank, then by default EPSOM = 0.1% of synchronous speed or rated speed for DC machines.

Card (2) of Class 2 data cards:



OMEGM ---- Initial condition of the mechanical speed in [rad/sec] or in
(1-14) [per unit].

LMUD ---- Unsaturated d-axis main inductances in [H] or in [per unit].
(15-23)

JSATD ---- Request for implementation of d-axis saturation if JSATD is
(29) set to 1. Leave blank if no d-axis saturation is desired.

REMARK: The quantities following JSATD in the data card can be all left blank if no d-axis saturation is desired. Otherwise these quantities pertain to specifications of the d-axis saturation curve as shown in the following figure:

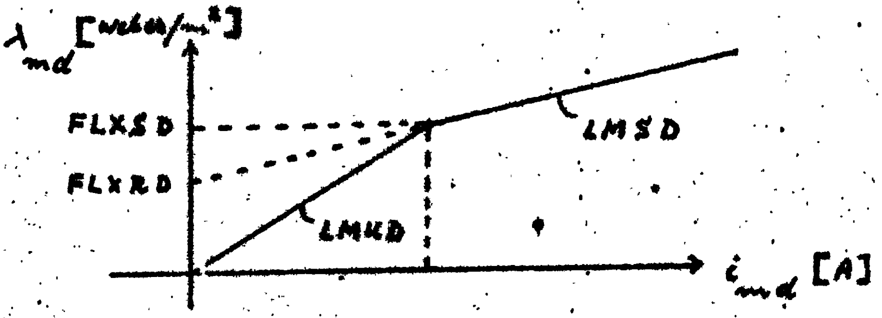


Fig. 1. d-axis saturation curve
Horizontal: d-axis excitation current
Vertical: d-axis main flux

It is to be noted that obviously -

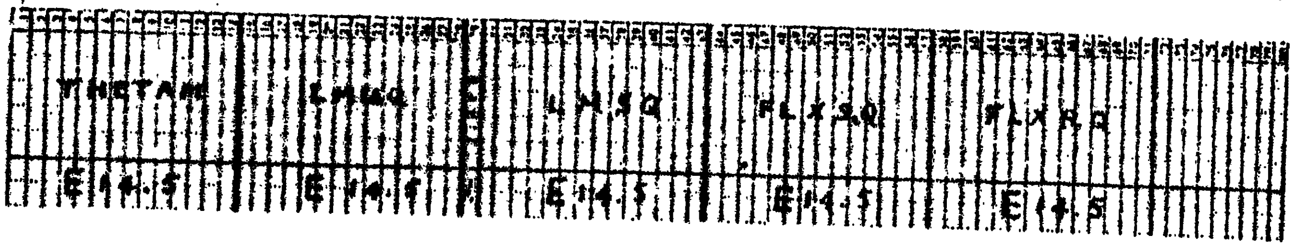
LMUD = slope of curve in unsaturated part
LMSD = slope of curve in saturated part

LMSD (30-43) ---- Leave blank if no d-axis saturation is desired. Otherwise, see REMARK pertaining to JSATD and Fig. 1.

FLXSD (44-57) ---- Leave blank if no d-axis saturation is desired. Otherwise, see REMARK pertaining to JSATD and Fig. 1.

FLXRD (58-71) ---- Leave blank if no d-axis saturation is desired. Otherwise, see REMARK pertaining to JSATD and Fig. 1.

Card (3) of Class 2 data cards:



THETAM (1-14) ---- Initial condition of rotor position with respect to stator in mechanical [rad]. For synchronous machines, i.e. JTYPE = 1 and 2, this angle is the torque angle in electrical [rad].

LMUQ (15-28) ---- Unsaturated q-axis main inductance in [H] or in [per unit].

JSATQ, LMSQ, FLXSQ, FLXRQ (29-71) -- All these quantities can be left blank, if no q-axis saturation effects is desired. Otherwise, since these q-axis saturation quantities are completely analog in their meaning with those of the d-axis, i.e., JSATD, LMSD, FLXSD, FLXRD, please consult card (2) where these quantities are documented.

16.3e Class 3 U.M. data cards (Coil-table):

After ending the U.M. class 2 data cards with a blank termination card, the U.M. class 3 data cards have to be set up. Each card of this class we will refer to as a coil-card in which all information about one single coil has to be specified. (that is why U.M. class 3 data cards really form a coil-table.) The data format of a coil card is as follows:

36K

RESIS	LLEAK	BUS1	BUS2	XTACS	[illegible]	CUR
E14.5	E14.5	A6	A6	A6	I	E14.5

RESIS (1-14) ---- Resistance in [Ω] or in [per unit].

REMARK: RESIS cannot be taken equal to 0.

LLEAK (15-28) ---- Leakage inductance in [H] or in [per unit].

BUS1 (29-34) ---- Node name of the Electrical Network to which one terminal of the coil is connected. Leave blank if local ground connection or no connection with the Electrical Network is desired.

BUS2 (35-40) ---- Node name of the Electrical Network to which the other terminal of the coil is connected. Leave blank if local ground connection or no connection with the Electrical Network is desired.

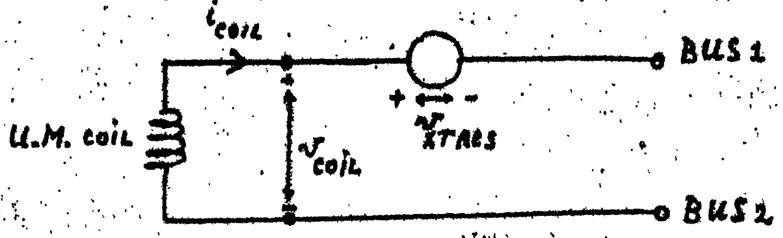
XTACS (41-46) ---- Name of TACS variable, which is used as a voltage source in series with the coil.

CUROUT (47) ---- Request for output of the coil current if set to 1; leave blank if no output is desired.

CUR (48-61) ---- Initial condition of the coil current in [A] or in [per unit].

General Rules with respect to the coil cards:

(1) The following sign-convention has to be realized in assigning BUS1, BUS2, XTACS and CUR :



Thus: *Positive coil current means that it goes from BUS2 to BUS1
*The terminal coil voltage is:

$$v_{coil} = v_{BUS1-BUS2} + v_{XTACS}$$

(2) The coil cards specifying the coils of one machine can not be mixed with coil cards of other machines. The different machines with their different groups of coil cards must be arranged in the same sequence as chosen in the machine-table (see Class 2 U.M. data cards), i.e., first the coil cards of UM-1, then coil cards of UM-2, etc.

(3) With respect to the sequence of coil cards belonging to one machine, the following rules apply:

3.1 First comes 3 mandatory coil cards representing the power coils in the sequence of coil A, coil B and coil C. If less than 3 power coils is needed, then insert blank cards for the non-used coils.

3.2 Then comes NCLD coil cards representing the d-axis excitation coils, with the value of NCLD as specified in the machine-table (see Class 2 U.M. data cards).

REMARKS: No coil cards nor blank cards are to be inserted if NCLD = 0.

3.3 Finally comes NCLQ coil cards representing the q-axis excitation coils, with the value of NCLQ as specified in the machine-table.

REMARKS: No coil cards nor blank cards are to be inserted if NCLQ = 0.

(4) Since currently the three-phase compensation restriction applies to the U.M., all U.M. machines to be used have to be electrically separated from each other. The "stub line" strategy can be applied to avoid this restriction, which is described elsewhere in this reference manual. Moreover, the consequence of the three-phase restriction to the external connections of coil terminals for one machine is as follows:

* The power coils can be all connected to each other in one electrical network, but cannot be connected to the excitation coils. Again use stub line or TACS element to avoid this restriction.

* Only the first three excitation coils can be connected to one and another in one electric network; if more than three excitation coils are used, then excitation coil number 4 and higher must be completely disconnected from each other. This restriction can be avoided also by using a stub line or a TACS element.

(5) Provide a blank termination card behind the last coil card of the last machine, indicating the termination of the U.M. data cards.

36K-2

16.3f OUTPUT LABLES

All U.M. output are labeled by two names:

- Upper label indicates the machine number
- Lower label indicates the corresponding variable.

Example:		
	UM-4 TQGEN	UM-4 IPA

The U.M. variables which can be requested for output are:

TQGEN ---- Electromechanical torque based on generator convention in [per unit] or [N.m].

OMEGM ---- Mechanical rotor speed in [rad/sec].

IPA,IPB,IPC -- Currents of the power coils A, B and C in [per unit] or [A].

Note: *For all types of direct current machines, the power (armature) coil current is indicated by IPC.

*For U.M. Type 6 and 7 (=single-phase A.C. machines, see their User's Guide), these labels indicate excitation currents.

IE_1,IE_2,etc. --Currents of the excitation coils in [per unit] or [A].

Note: *For U.M. Type 4 (induction machine, 3-phase stator and rotor), the 3-phase rotor currents in coils B, C and A are respectively indicated by IE_1, IE_2, IE_3.

*For U.M. Type 6 and 7 (single-phase A.C. machines, see their User's Guide), these labels indicate the power coil currents.

Note on Coil-Parameters

The purpose of this note is to supply conversion formulas for users who have data of coil-parameters specified in terms of self and mutual inductances, which due to the current UM data input have to be expressed in terms of leakage and main inductances. It is possible that future development will include an automatic preprocessor for this purpose.

In the next discussion the following notation will be adopted:

$L_{\ell i}$ = leakage inductance of coil i [H]

L_{mi} = main inductance of coil i [H]

R_i = resistance of coil i [Ohm]

L_{ii} = self inductance of coil i [H]

L_{ij} = mutual inductance of coil i and coil j [H]

It is to be noted that the conversion formulas which will be derived, are only valid if the SI unit system is used. If the parameters are in the Per Unit (pu) system, then since there exists several per unit systems, it is suggested to consult for example the book: FOUAD and ANDERSON, "Power System Stability and Control", Iowa State University Press, pp. 92-104, 1977. The UM coil-parameters involved are:

L_{md} = LMUD in card (2) of class 2 data cards

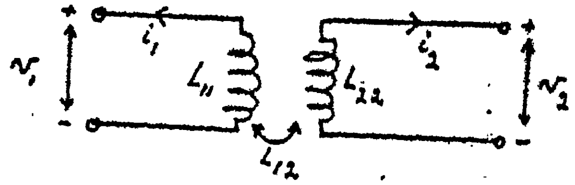
L_{mq} = LMUQ in card (3) of class 2 data cards

L_{ℓ} = LLEAK in class 3 data cards

R = RESIS in class 3 data cards

2-Coil System:

The idea of how to obtain the leakage and main inductances from the self and mutual inductances will be illustrated for a transformer. Although a transformer is not an electrical machine, the basic mechanism to derive the desired conversion formulas is essentially not different. This is because an inductance is a parameter describing the relation between a coil current and the magnetic flux enclosed by the coil contour. By considering a 2 coil transformer, the central idea can be most easily understood.



For the transformer as shown schematically in the figure above, the voltage equations can be written as:

$$v_1 = - R_1 i_1 - \frac{d\lambda_1}{dt}$$
$$v_2 = - R_2 i_2 - \frac{d\lambda_2}{dt} \qquad (1)$$

The current-flux relation in terms of self-inductances, L_{11} and L_{22}, and of mutual inductance L_{12}, can be expressed as:

36K-f

$$\begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \qquad (2)$$

with: $L_{12} = L_{21} = \frac{N_1 N_2}{R_m}$

$$L_{11} = L_{\ell 1} + \frac{N_1^{\,2}}{Rm} \qquad (3)$$

$$L_{22} = L_{\ell 2} + \frac{N_2^{\,2}}{Rm}$$

where N = number of turns and R_m = magentic reluctance.

To express the equations in terms of leakage and mutual inductances, one of the "sides" of the transformer has to be reduced (refered) to the other. Let us reduce the secondary side (index 2) to the primary side (index 1). Then introduce the following reduction factor, which for transformers specifically is called turn ratio:

$$a_2 = \frac{N_1}{N_2} \qquad (4)$$

Now rewrite the voltage equations Eqn (1) as:

$$v_1 = -R_1 i_1 - \frac{d\lambda_1}{dt}$$

$$\qquad (5)$$

$$a_2 v_2 = -(a_2^{\,2} R_2)(i_2/a_2) - \frac{d}{dt}(a_2 \lambda_2)$$

and also rewrite the current-flux relations Eqn (2) as:

$$\begin{bmatrix} \lambda_1 \\ a_2 \lambda_2 \end{bmatrix} = \begin{bmatrix} L_{11} & a_2 L_{12} \\ a_2 L_{12} & a_2^{\,2} L_{22} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2/a_2 \end{bmatrix} \qquad (6)$$

Now by introducing the so-called reduced*secondary variables:

$v_2' = a_2 v_2$

$i_2' = i_2 / a_2$ (7)

$R_2' = a_2^{\,2} R_2, \; L_{22}' = a_2^{\,2} L_{22}$

and realizing from Eqn (3) that

$$L_{m1} = a_2 L_{12} \qquad (8)$$

the transformer can be described by the equations:

$$\begin{aligned} v_1 &= -R_1 i_1 - \frac{d\lambda_1}{dt} \\ v_2' &= -R_2' i_2' - \frac{d\lambda_2'}{dt} \end{aligned} \qquad (8)$$

$$\begin{bmatrix} \lambda_1 \\ \lambda_2' \end{bmatrix} = \begin{bmatrix} L_{11} & L_{m1} \\ L_{m1} & L_{22}' \end{bmatrix} \begin{bmatrix} i_1 \\ i_2' \end{bmatrix} \qquad (9)$$

Now at this point L_{11} and L_{22}' can be partitioned as:

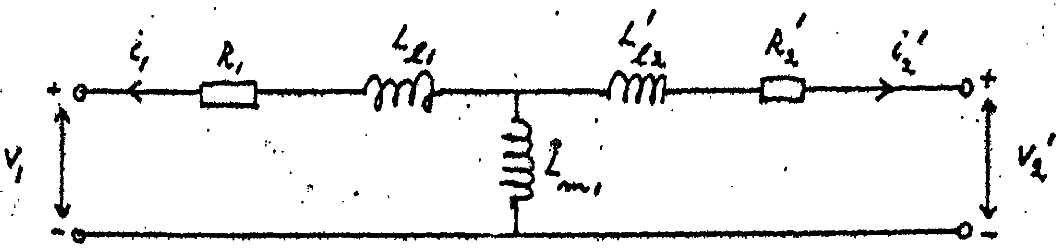
$$\begin{aligned} L_{11} &= L_{\ell 1} + L_{m1} \\ L_{22}' &= a_2^2 L_{22} = a_2^2 L_{\ell 2} + L_{m1} = L_{\ell 2}'' + L_{m11} \end{aligned}$$

so that from Eqn (9) we have the current-flux relation:

$$\begin{aligned} \lambda_1 &= L_{\ell 1} i_1 + L_{m1}(i_1 + i_2') \\ \lambda_2' &= L_{\ell 2}' i_2' + L_{m1}(i_1 + i_2') \end{aligned}$$

The leakage inductance is then identified as $L_{\ell 1}$ and $L_{\ell 2}'$, and both coils have now the same main inductance L_{m1}.

On the basis of the formulation of Eqn (8) and Eqn (10) the transformer can be interpreted as having the following connected network:



Several conclusions can now be made:

(a) Physically this formulation corresponds with the concept of 2 coils linked by a main flux in addition to their individual leakage fluxes. The usefulness of this formulation to numerical implementation is the fact that practically only the main inductance L_{m1} is susceptive to changes if the magnetic material becomes saturated.

(b) If the reduction factor a_2 is given, then the conversion formulas needed to obtain the main and leakage inductances from given self and mutual inductances, are:

$$\begin{aligned} L_{m1} &= a_2 L_{12} \\ L_{\ell 1} &= L_{11} - L_{m1} \\ L'_{\ell 2} &= a_2^2 L_{22} - L_{m1} \end{aligned} \tag{11}$$

(c) If the reduction factor is not given, then the following approximated conversion formulas is suggested:

$$\begin{aligned} L_{m1} &= 0.9\, L_{11} \quad , \quad L_{\ell 1} = 0.1\, L_{11} \\ a_2 &= L_{m1} / L_{12} \\ L'_{\ell 2} &= a_2^2 L_{22} - L_{m1} \end{aligned} \tag{12}$$

Sometimes the rated currents I_{1B} and I_{2B} are given. In this case the reduction factor can be approximated by:

$$a_2 = \frac{I_{2B}}{I_{1B}} \quad \left(\text{or } \frac{V_{1B}}{V_{2B}}\right) \tag{13}$$

Then the Conversion formulas of Eqn (11) can be used to obtain the desired main and leakage inductances.

(d) All parameters and variables of the secondary side, including the network to which it is connected, has to be reduced (see Eqn. 7), i.e.

- their voltages are to be multiplied by a_2.
- their currents are to be divided by a_2.
- their resistances and inductances are to be multiplied by a_2^2.

4-Coil System:

The concept of the 2-coil system linked by a main flux in addition to their individual leakage flux, can be easily extended to the general n-coil system. We will show this by considering a 4-coil system, and again we are interested to find the conversion formulas to obtain main and leakage inductances from self and mutual inductances.

In terms of self and mutual inductance, the 4-coil system is described by:

- the voltage equations:

$$
\begin{aligned}
v_1 &= -R_1 i_1 - \frac{d\lambda_1}{dt} \\
v_2 &= -R_2 i_2 - \frac{d\lambda_2}{dt} \\
v_3 &= -R_3 i_3 - \frac{d\lambda_3}{dt} \\
v_4 &= -R_4 i_4 - \frac{d\lambda_4}{dt}
\end{aligned}
\qquad (14)
$$

- the current-flux relation:

$$
\begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \end{bmatrix}
=
\begin{bmatrix} L_{11} & L_{21} & L_{31} & L_{14} \\ L_{12} & L_{22} & L_{32} & L_{24} \\ L_{13} & L_{23} & L_{33} & L_{34} \\ L_{14} & L_{24} & L_{34} & L_{44} \end{bmatrix}
\begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \end{bmatrix}
; \; L_{ij} = L_{ji} \qquad (15)
$$

- the inductances in terms of the number of turns N and magnetic reluctance R_m:

$$
\begin{aligned}
L_{ij} &= \frac{N_i N_j}{R_m} \quad \text{for } i \neq j \\
L_{ii} &= L_{li} + \frac{N_i^2}{R_m} \quad \text{for } i = 1, 2, 3, 4
\end{aligned}
\qquad (16)
$$

Now in analogy with the 2-coil system, we reduce coil 2, 3 and 4 to the "primary" coil 1. This requires the introduction of 3 reduction factors (compare with Eqn. 4):

$$a_2 = \frac{N_1}{N_2}, \quad a_3 = \frac{N_1}{N_3}, \quad a_4 = \frac{N_1}{N_4} \tag{17}$$

These reduction factors are implemented in the system equations in the same way as for the 2-coil system shown in Eqn. (5) and (6):

* the voltage equations:

$$\begin{aligned} V_1 &= -R_1 i_1 - \frac{d}{dt}(\lambda_1) \\ a_2 V_2 &= -(a_2^2 R_2)(i_2/a_2) - \frac{d}{dt}(a_2 \lambda_2) \\ a_3 V_3 &= -(a_3^2 R_3)(i_3/a_3) - \frac{d}{dt}(a_3 \lambda_3) \\ a_4 V_4 &= -(a_4^2 R_4)(i_4/a_4) - \frac{d}{dt}(a_4 \lambda_4) \end{aligned} \tag{18}$$

* the current-flux relation:

$$\begin{bmatrix} \lambda_1 \\ a_2 \lambda_2 \\ a_3 \lambda_3 \\ a_4 \lambda_4 \end{bmatrix} = \begin{bmatrix} L_{11} & a_2 L_{12} & a_3 L_{13} & a_4 L_{14} \\ a_2 L_{12} & a_2^2 L_{22} & a_2 a_3 L_{23} & a_2 a_4 L_{24} \\ a_3 L_{13} & a_2 a_3 L_{23} & a_3^2 L_{33} & a_3 a_4 L_{34} \\ a_4 L_{14} & a_2 a_4 L_{24} & a_3 a_4 L_{34} & a_4^2 L_{44} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2/a_2 \\ i_3/a_3 \\ i_4/a_4 \end{bmatrix} \tag{19}$$

Now at this point it is important to observe that due to Eqn. (16), all off-diagonal terms of the inductance matrix above are equal to the main inductance L_{m1}. In fact this is the reason of introducing the reduction factors. Thus:

$$L_{m1} = a_2 L_{12} = a_3 L_{13} = a_4 L_{14} = a_2 a_3 L_{23} = a_2 a_4 L_{24} = a_3 a_4 L_{34} \tag{20}$$

Moreover, again due to Eqn. (16) we have for the diagonal terms:

$$\begin{aligned} L_{11} &= L_{\ell 1} + L_{m1} \\ a_2^2 L_{22} &= a_2^2 L_{\ell 2} + L_{m1} \\ a_3^2 L_{33} &= a_3^2 L_{\ell 3} + L_{m1} \\ a_4^2 L_{44} &= a_4^2 L_{\ell 4} + L_{m1} \end{aligned} \tag{21}$$

Finally considering the results of Eqn. (18) to (21) we introduce the reduced variables for coil 2, 3 and 4 according to the same rule as for the 2-coil system. For i = 2, 3, 4, define:

$$
\begin{aligned}
V_i' &= a_i V_i \\
i_i' &= i_i / a_i \qquad\qquad\qquad\qquad\qquad (22) \\
R_i' &= a_i^2 R_i \quad , \quad L_{ii}' = a_i^2 L_{ii} \quad , \quad L_{\ell i}' = a_i^2 L_{\ell i}
\end{aligned}
$$

Then our 4-coil system equations become:

* the voltage equations:

$$
\begin{aligned}
V_1 &= - R_1 i_1 - \frac{d}{dt}(\lambda_1) \\
V_2' &= - R_2' i_2' - \frac{d}{dt}(\lambda_2') \qquad\qquad (23) \\
V_3' &= - R_3' i_3' - \frac{d}{dt}(\lambda_3') \\
V_4' &= - R_4' i_4' - \frac{d}{dt}(\lambda_4')
\end{aligned}
$$

* the current flux relations:

$$
\begin{aligned}
\lambda_1 &= L_{\ell 1} i_1 + L_{m1}(i_1 + i_2' + i_3' + i_4') \\
\lambda_2' &= L_{\ell 2}' i_2' + L_{m1}(i_1 + i_2' + i_3' + i_4') \qquad (24) \\
\lambda_3' &= L_{\ell 3}' i_3' + L_{m1}(i_1 + i_2' + i_3' + i_4') \\
\lambda_4' &= L_{\ell 4}' i_4' + L_{m1}(i_1 + i_2' + i_3' + i_4')
\end{aligned}
$$

Conclusions we can make are:

(a) Basically the results for a 4-coil system are just extensions of the 2-coil system, in that we are able to obtain a main flux concept as represented by one main inductance L_{m1} in addition to the individual leakage fluxes of each coil as represented by $L_{\ell 1}$, $L_{\ell 2}'$, $L_{\ell 3}'$, and $L_{\ell 4}'$.

(b) The system formulation in terms of main and leakage inductances requires the reduction of all coils to one coil, which in above examples is coil 1. This means that all coils (plus networks connected to these coils) other than coil 1 should have:

- * their voltages multiplied by the corresponding reduction factor.
- * their currents divided by the corresponding reduction factor.
- * their resistances and inductances multiplied by the corresponding square of the reduction factor.

(c) If all reduction factors are given, then the conversion formulas to obtain the main and leakage inductances from given self and mutual inductances are:

$$\begin{aligned} L_{m1} &= a_2 L_{12} \\ L_{\ell 1} &= L_{11} - L_{m1} \\ L'_{\ell i} &= a_i^2 L_{ii} - L_{m1} \end{aligned} \qquad (25)$$

(d) If the reduction factors are not given, then the following approximated conversion is suggested:

$$L_{m1} = 0.9\, L_{11} \quad , \quad L_{\ell 1} = 0.1\, L_{11} \qquad (26)$$

$$\left.\begin{aligned} a_i &= L_{m1} / L_{1i} \\ L'_{\ell i} &= a_i^2 L_{ii} - L_{m1} \end{aligned}\right\} \text{for } i = 2, 3, 4$$

(e) Sometimes the rated currents I_{iB} are given. In this case the reduction factors can be approximated by :

$$a_i \approx \frac{I_{iB}}{I_{1B}} \quad \left(\text{or } \frac{V_{1B}}{V_{iB}}\right) \quad \text{for } i = 2, 3, 4 \qquad (27)$$

Having determined these reduction factors, the formulas in Eqn. (25) can be used to obtain the main and leakage inductances.

IF only I_{1B} and I_{2B} are given, then find all a_i from:

$$a_2 \approx \frac{I_{2B}}{I_{1B}} \quad \left(\text{or } \frac{V_{1B}}{V_{2B}}\right).$$

Then find $L_{m1} = a_2 L_{12}$

Then find a_3 and a_4 from: $a_i = L_{m1} / L_{1i}$

Extension to Electric Machines

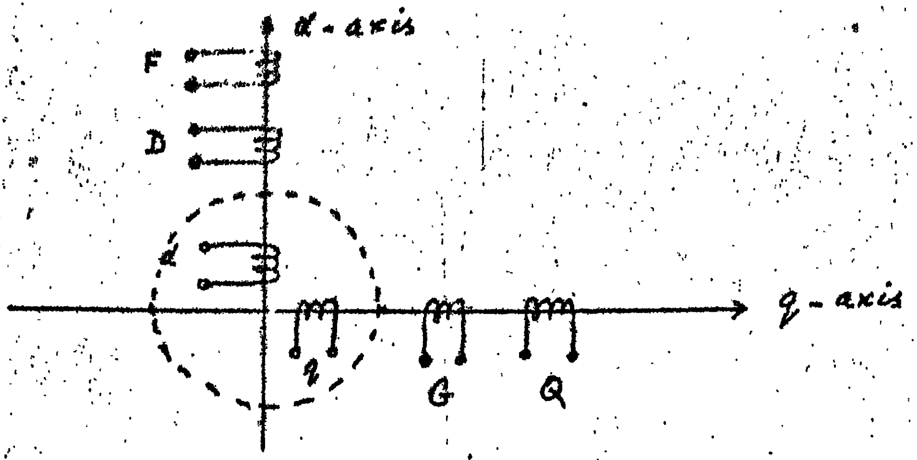
The concept of coils on the same magnetic shaft as linked by a main flux in addition to the individual leakage fluxes can be carried over to the coil-arrangement of electric machines. In the Park domain these magnetic shafts are the direct and quadrature axis. Then for each of these axis, the conversion formulas as given in Eqn. (25), (26), and (27) can be applied. A rigorous account of the reduction process to the power side d- and q-coil can be found for instance in: White and Woodson, "Electromechanical Energy Conversion", John Wiley.

Basically the main and leakage inductances are introduced in the same way as explained here in this note, except that proper account have to be taken of the winding distribution factors rather than by considering the number of turns only.

Let us now consider the case that all excitation coils are coils which have magnetic shafts either in the direct (d)-axis or in the quadrature (q)-axis or in both axis. See later special notes on Direct Current machines and UM type 4. It is convenient to formulate the main and leakage inductances on the basis of reduction of all excitation coils to the power coils which are positioned on the same magentic shaft.

If the power side is a three-phase system, then their equivalent coil-parameters in the Park domain have to be determined first. This is a well-known procedure, and let us call these equivalent power coils the o-coil, d-coil, and q-coil. The o-coil is decoupled from all other coils, the magnetic shaft of the d-coil is in the direct (d) axis and the magnetic shaft of the q-coil is in the quadrature (q) axis.

Now let us consider the following example. Suppose that we have 4 excitation coils, 2 coils D and F on the d-axis and 2 coils Q and G on the q-axis. The system is schematically shown in the figure below:



d- and q-coils : power coils ; F, D, G, Q-coils : excitation coils

Now suppose that the user has available all self and mutual inductances. Then in order to find the main and leakage inductances as required by the UM, the same approach can be taken as outlined for the 4-coil system.

(a) If the reduction factors are given:

$$L_{md} = a_F L_{dF} \qquad L_{mq} = a_G L_{qF}$$
$$L_{ld} = L_{dd} - L_{md} \qquad L_{lq} = L_{qq} - L_{mq}$$
$$L'_{lF} = a_F^2 L_{FF} - L_{md} \qquad L'_{lG} = a_G^2 L_{GG} - L_{mq}$$
$$L'_{lD} = a_D^2 L_{DD} - L_{md} \qquad L'_{lQ} = a_Q^2 L_{QQ} - L_{mq}$$

Note: The prime on some of the variables indicates that they are reduced variables.

(b) If the reduction factors are not given, then the following approximated conversion is suggested.

$$L_{md} = 0.9\, L_{dd} \qquad L_{mq} = 0.9\, L_{qq}$$
$$L_{ld} = 0.1\, L_{dd} \qquad L_{lq} = 0.1\, L_{qq}$$
$$\left.\begin{aligned} a_i &= L_{md}/L_{di} \\ L'_{li} &= a_i^2 L_{ii} - L_{md} \end{aligned}\right\} \text{for } i = D, F \qquad \left.\begin{aligned} a_i &= L_{mq}/L_{qi} \\ L'_{li} &= a_i^2 L_{ii} - L_{mq} \end{aligned}\right\} \text{for } i = G, Q$$

If the rated currents I_{iB} of the coils are given, then the reduction factors can be approximated by:

$$a_F \approx \frac{I_{FB}}{I_{dB}} \quad \left(\text{or } \frac{V_{dB}}{V_{FB}}\right) \Rightarrow \text{Find } L_{md} = a_F L_{dF} \rightarrow \text{Find } a_D = L_{md}/L_{dD}$$

$$a_G \approx \frac{I_{GB}}{I_{qB}} \quad \left(\text{or } \frac{V_{qB}}{V_{GB}}\right) \rightarrow \text{Find } L_{mq} = a_G L_{qG} \rightarrow \text{Find } a_Q = L_{mq}/L_{qQ}$$

Consequently the main and leakage inductances can again be found from the formulas of case (a).

(c) It is elucidating to see that the current-flux relation is for the d-axis coils:

$$\lambda_d = L_{ld} i_d + L_{md} (i_d + i_F' + i_D')$$

$$\lambda_F' = L_{lF}' i_F' + L_{md} (i_d + i_F' + i_D')$$

$$\lambda_D' = L_{lD}' i_D' + L_{md} (i_d + i_F' + i_D')$$

and for the q-axis coils:

$$\lambda_q = L_{lq} i_q + L_{mq} (i_q + i_G' + i_Q')$$

$$\lambda_G' = L_{lG}' i_G' + L_{mq} (i_q + i_G' + i_Q')$$

$$\lambda_Q' = L_{lQ}' i_Q' + L_{mq} (i_q + i_G' + i_Q')$$

(d) It is re-emphasized that all parameters and variables of the excitation coils including the network to which they are connected, have to be reduced according to rules as explained earlier:

* their voltages are to multiplied by the reduction factor.

* their currents are to divided by the reduction factor.

* their resistances and inductances multiplied by the square of the reduction factor.

The power coil variables and parameters remain unchanged in the reduction process.

Special Note on UM Type 4

Since this type has a three-phase excitation system, it does not directly fit the general discussion as held earlier, where all excitation coils are supposed to have magnetic shafts in line with the direct and quadrature axis. This is solved internally in the UM program by an extended Park transformation which in effect creates 3 equivalent power coils and 3 equivalent excitation coils: 2 zero coils which are decoupled from all other coils, the other 4 coils in the direct and quadrature axis each with 1 power coil and 1 excitation coil. The user of the program needs not to bother about this transformation, it is mentioned here to indicate that as a result the general comments made earlier hold and can be applied. Since however the induction machine is balanced in its design with respect to its three a, b, c phases, we will present the very simple conversion formulas here.

Let us use the following notation for the given self and mutual inductances of the machine.

L^{SS} = stator self-inductance

M^{SS} = mutual inductance between 2 stator coils

L^{RR} = rotor self-inductance

M^{RR} = mutual inductance between 2 rotor coils

M^{SR} = maximum value of mutual inductance between stator and a rotor coil of the same phase.

The power coils are the stator coils and the excitation coils are the rotor coils.

The main and leakage indunctances as required by the UM can be obtained as follows.

(a) Realize first that the real a,b,c coils have to be transformed to equivalent o,d,q coils for both the stator and rotor side. The self and mutual inductances of these equivalent coils are:

* self inductance of stator o-coil: $L_o^{SS} = L^{SS} - 2M^{SS}$

- self inductance of rotor o-coil: $L_o^{RR} = L^{RR} - 2M^{RR}$
- self inductance of stator d-coil and stator q-coil:

  $L_d^{SS} = L_q^{SS} = L^{SS} + M^{SS}$
- $L_d^{RR} = L_q^{RR} = L^{RR} + M^{RR}$
- mutual inductance between stator and rotor coils on the same magnetic shaft (either d-or q-axis): $L_{dd}^{RS} = L_{qq}^{RS} = \sqrt{\frac{3}{2}}\, M^{SR}$

(b) If the reduction factor a is given, then the conversion formulas to obtain the main and leakage inductances can be obtained by applying the general theory discussed earlier, to give:

$$L_{md} = L_{mq} = a\sqrt{\frac{3}{2}}\, M^{SR}$$

$$L_{\ell d}^{S} = L_{\ell q}^{S} = (L^{SS} + M^{SS}) - L_{md}$$

$$L_{\ell d}^{R'} = L_{\ell q}^{R'} = a^2(L^{RR} + M^{RR}) - L_{md}$$

The variables supplied by a prime are reduced variables.

(c) If the reduction factor is not given, the conversion formulas can by approximated by:

$$L_{md} = L_{mq} = 0.9\,(L^{SS} + M^{SS})$$

$$L_{d\ell}^{S} = L_{q\ell}^{S} = 0.1\,(L^{SS} + M^{SS})$$

$$a = (L^{SS} + M^{SS}) \,/\, (\sqrt{\tfrac{3}{2}}\, M^{SR})$$

$$L_{d\ell}^{R'} = L_{q\ell}^{R'} = a^2(L^{RR} + M^{RR}) - L_{md}$$

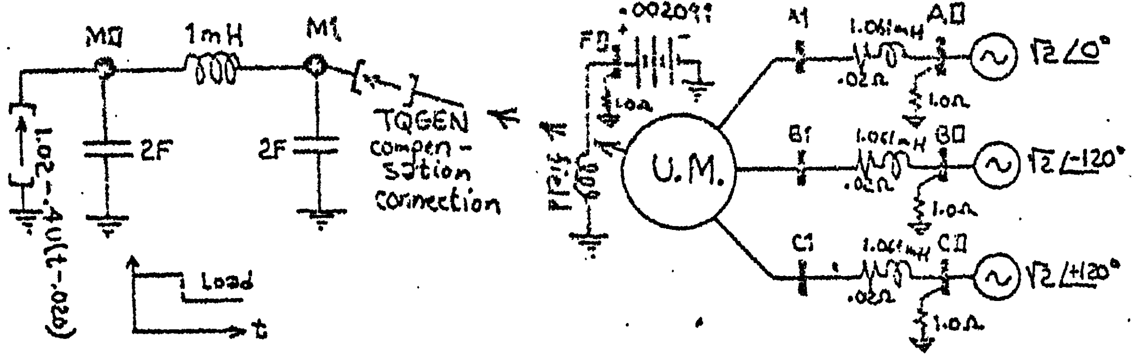
(d) All excitation variables have to be reduced in the same sense as described in previous discussion. It is to be noted that the zero excitation coil has to be reduced also. Thus: $L_o^{R'} = a^2 L_o^{RR}$

Special Note on DC Machines

For some of the types of DC machines the situation arises that we might not have both a power coil and an excitation coil on the same magnetic axis. In this case the partitioning into main and leakage flux can be made arbitrarily without any numerical consequences.

7.63C ILLUSTRATIVE U.M. APPLICATION AS 3-PHASE SYNCHRONOUS MACHINE

To show the user the structure of a data case that involves U.M. modeling, I present Hian's synchronous machine problem. EMTP data is documented by the output of the following page, which corresponds to th electric circuit shown here:



In th semi-random order that observations about this data occur to me, I offer the following:

Point 1 : The first four branches go from the four voltage sources to ground. They have no functional usage other than ensuring connectivity to ground, I guess. They do not affect the mathematical solution, note.

Point 2 : The field winding is connected to the electric network through bus "BUS-F0" . This is a compensation connection, even though all Hian wanted was a dc voltage. Why? Later, when the TACS connection is debugged, a dc source from TACS can be connected for this purpose, and the compensation (and electric network connection) can be spared.

Point 3 : We are here using the new (since "M21.") feature that allows the user to punch "BLANK " in columns 1-6, and have the resultant data card appear as a blank card to the EMTP. Thus one can name the blank cards, which is sometimes less confusing. "CIMAGE" blanks out such special records.

Point 4 : The second data card serves to divide the total working space of List 25 (3700 cells) among the four different U.M. tables. The key word is "ABSOLUTE U.M. DIMENSIONS" , named by analogy to the corresponding card for TACS ("ABSOLUTE TACS DIMENSIONS"; see Vol. VIII, 27 January 1979, page PROV-19. This card requests a limit of 20 coils (for all components of the U.M. tables), a limit of 2 machines, etc. This is absolute allocation: a specific number. The card is now mandatory. Later, we shall make it optional (as with TACS), and we shall also provide a "RELATIVE U.M. DIMENSIONS" option, just as with TACS. The interpretation shows that we are using only 317 of the 3700 cells which are available.

362-1

SRFH-4

```
ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP), DIGITAL (DEC) VAX-11/780 TRANSLATION AS USED BY BPA IN PORTLAND, OREGON  97208
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS.)= 04/06/80  23.33.20  ANY PLOTS BEAR SAME FIGURES.                VERSION = "M27."
IF IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE 564-PAGE EMTP USER'S MANUAL DATED NOVEMBER, 1977.
INDEPENDENT LIST LIMITS FOLLOW,   TOTAL LENGTH OF   /LABEL/   EQUALS 199563  INTEGER WORDS.        703  1050  2500     30  9500
   125  6100  5000    50   300   100   140     5  9000   400     9    4    30  6000   500    72   250  3000    6  3700
-----------------------------------------------------------------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA I INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER,
                                                  0         1         2         3         4         5         6         7         8
                                                  0         0         0         0         0         0         0         0         0
-----------------------------------------------------------------------------------------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.              IBEGIN NEW DATA CASE
U.M. TABLE SIZES.     20     2    50    100       IABSOLUTE U.M. DIMENSIONS, 20, 2, 50, 100
COMMENT CARD.                                     IC AGNOSTIC           0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 8
MISC. DATA.     0.100E-02   0.100E+01   0.000E+00 I     .001      1.0
MISC. DATA.      1    1  0  0  1  -1  0  2  0  0  I       1         1         0        00         1        -1                 2
REQUESTED CHANGES IN SOLUTION PRINTOUT FREQUENCY. I       5         5        20        20       100       100
SERIES R-L-C.     0.100E+01  0.0[illegible]  0.000E+00 I 0       BUS-F0                1.0
SERIES R-L-C.     0.100E+01  0.0[illegible]  0.000E+00 I 0       BUS-A0                1.0
SERIES R-L-C.     0.100E+01  0.0[illegible]  0.000E+00 I 0       BUS-B0                1.0
SERIES R-L-C.     0.100E+01  0.0[illegible]  0.000E+00 I 0       BUS-C0                1.0
SERIES R-L-C.     0.200E-01  0.1[illegible]  0.000E+00 I 0BUS-[illegible]BUS-A0          0.02  1.0610
REFERENCE BRANCH.    COPY  "BUS-[illegible]  TO "BUS-A0"   I 0BUS-[illegible]BUS-B0BUS-A1BUS-A0                                         1
REFERENCE BRANCH.    COPY  "BUS-[illegible]  TO "BUS-A0"   I 0BUS-[illegible]BUS-C0BUS-A1BUS-A0                                         1
SERIES R-L-C.     0.000E+00  0.[illegible]  0.200E+07 I 0BUS-M1                                  2.0086                             1
SERIES R-L-C.     0.000E+00  0.[illegible]  0.200E+07 I 0BUS-M0                                  2.0086                             1
SERIES R-L-C.     0.000E+00  0.[illegible]  0.000E+00 I 0BUS-M0BUS-M1                          1.                                   1
BLANK CARD TERMINATING BRANCH CARDS.              IBLANK CARD ENDING BRANCHES.
BLANK CARD TERMINATING SWITCH CARDS.              IBLANK CARD ENDING SWITCHES.
SOURCE.      0.21E-02  0.00E+00  0.[illegible]  -0.10E+01 I11BUS-F0  0.002091                                         -1.0
SOURCE.      0.10E+01  0.00E+00  0.[illegible]   0.00E+00 I11BUS-M0-1        1.02
SOURCE.     -0.40E+00  0.00E+00  0.[illegible]   0.20E-01 I11BUS-M0-1         -.4                                          .020
SOURCE.      0.14E+01  0.60E+02  0.[illegible]  -0.10E+01 I14BUS-A0  1.41421356 60.0       0.0                           -1.
SOURCE.      0.14E+01  0.60E+02  -[illegible]  -0.10E+01 I14BUS-B0  1.41421356 60.0    -120.0                           -1.
SOURCE.      0.14E+01  0.60E+02  [illegible]  -0.10E+01 I14BUS-C0  1.41421356 60.0     120.0                           -1.
U.M. DATA BEGINS.  LIST-25 C[illegible] USED =  317   I19
 BEGIN U.M.  INPU =     1                         I1
FIRST OF CARD SPLIT,    1     2                   I 1 2 1111BUS-M1          1 1786.98
2ND OF SPLIT,   0.10000E+01   [illegible]E+01     0 I1.0             1.550          0 0.3              .5          .9
3RD OF SPLIT,   0.25059E+01   [illegible]E+01     0 I2.5086665       1.490          0
BLANK CARD ENDING MACHINE TA[illegible]           IBLANK CARD ENDING U.M.  MACHINE-TABLE CARDS.
COIL   1.   0.00000E+00   0.[illegible]     1     I0.0             0.0            BUS-A1            1  1.3960
COIL   2.   0.10960E-02   0.[illegible]     1     I0.001096        0.150          BUS-B1            1 -0.95877
COIL   3.   0.10960E-02   0.[illegible]     1     I0.001096        0.150          BUS-C1            1 -0.42721
COIL   4.   0.74000E-03   0.[illegible]     1     I0.00074         0.101          BUS-F0            1 -2.326
COIL   5.   0.13100E-01   0.[illegible]-01  1     I0.0131          0.055                            1
COIL   6.   0.54000E-01   0.[illegible]-01  1     I0.0540          0.036                            1
BLANK CARD ENDING COIL TAB[illegible]             IBLANK CARD ENDING U.M.  COIL-TABLE CARDS.
BLANK CARD TERMINATING SOU[illegible]             IBLANK CARD ENDING SOURCES.
NODE VOLT INIT COND.  0.155[illegible]  0.000E+00    0.0 I 2BUS-A1 1.55413
NODE VOLT INIT COND. -0.30[illegible]   0.000E+00        I 2BUS-B1 -0.30745
NODE VOLT INIT COND. -0.12[illegible]   0.000E+00        I 2BUS-C1 -1.25677
NODE VOLT INIT COND.  0.14[illegible]   0.000E+00        I 2BUS-A0 1.41421356
NODE VOLT INIT COND. -0.70[illegible]   0.000E+00        I 2BUS-B0 -0.70710678
NODE VOLT INIT COND. -0.70[illegible]   0.000E+00        I 2BUS-C0 -0.70710678
NODE VOLT INIT COND.  0.20[illegible]   0.000E+00        I 2BUS-F0 0.002091
NODE VOLT INIT COND.  0.100[illegible]  0.000E+00        I 2BUS-M0 1.0
NODE VOLT INIT COND.  0.100[illegible]  0.000E+00        I 2BUS-M1 1.0
LINEAR I.      0.1385E+01  0.0000E+00  0.0000E+00 I 3BUS-A1BUS-A0 1.38494
LINEAR I.     -0.9579E+00  0.0000E+00  0.0000E+00 I 3BUS-B1BUS-B0 -0.95793
```

SRFH-5 357

This is most encouraging (317 cells for a 3-phase synchronous machine is nothing) .... though not quite the full story. Remember that the [illegible]ing system shows up as a ladder network on the electric [illegible] (so is not counted here), and [illegible] also is [illegible] overhead for working arrays of [illegible] dimensions [illegible]. This latter item will [illegible] increase [illegible] space on our map (if [illegible]tively count [illegible] with the increased code size) which [illegible] considered later.

Point 5 : The third [illegible] card is a comment card (before being disabled, we had a "[illegible]GNOSTIC" card). This is a change from "M21." versions: [illegible] is required in column 2, after the "C".

Point 6 : The infinite bus is "BUS-A0", etc. Note that it is of frequency 60 Hz, and amplitude SQRT(2.0). Clearly, Hian is operating in per unit, then. This had better not be a requirement, however. I will check this point with Hian (I confess never to have raised the subject before, which is somewhat of an oversight).

Point 7 : The values for the masses and the springs (capacitors and inductors) are quite arbitrary; they bear little relation to any known reality. This aspect (realistic shaft system modeling) is to be considered when correlation with the existing EMTP S.M. modeling for the Allis Chalmers or IEEE SSR Benchmark test cases is attempted. Later, Hian chose masses (capacitors) of 2.0 Farad, and I simply adjusted the spring (inductor) to 1.E-3 Henry so as to produce a reasonable resonant frequency of several Hertz.

Point 8 : The U.M. data is an EMTP source by classification, of type code 19. As presently set up, all U.M. components must be in order (contiguous data cards), following the single Type-19 request card. Nothing else is required on the request card, which simply transfers control to Hian's input routine "UMDATA" of overlay 5, where all U.M. data input actually occurs. Note that the U.M. data is by classes: first three data cards associated with the U.M. machine table (the machine as a whole), terminated by a blank card. My feeble interpretations like "FIRST OF CARD SPLIT", "2ND OF SPLIT", etc., merely reflect ignorance as to what the data actually is. The "split" comes from the fact that Hian originally read all of this data with a single READ, which I converted to three CALL CIMAGE and DECODE usages. Next come the coil cards, one for each coil of the machine. This is conceptually a little more obvious. Here Hian must input parameters of the coil (e.g., resistance), and its connection to the electric network and/or TACS. It looks to me like Hian has only three rotor coils (3 armature coils are required by the 3-phase machine, and 6-3=3), though an arbitrary number are permitted. The six coil cards are terminated by a blank card, ending the U.M. data (for this one-machine case). But why is there not a blank card ending U.M. components, after the blank card ending coils? I will have to check this (maybe we can not now use over one!).

Point 9 : Next come initial conditions for all electric network nodes and branches. This is a major inconvenience occasioned by lack of a steady-state connection. Yet I do not believe that

361-3

SRFH-6

this is a requirement. For Hian, this worked well; he set it up once, and then used it over and over. Very clean, for this usage. But a real burden for the production user. We should be able to use the phasor solution capability of the program automatically. Just as Herb and Al used to dump trapped charge on a transmission line by using [illegible]-Hz sinusoidal sources that would be disconnected on the first time step, so three extra Type-14 sinusoidal sources and connected switches should do the job for the [illegible]. Note that this does not automatically initialize the U.M. itself (the original problem), but at least it does handle the electric network. On the page 4 listing, note that not all initial condition cards are shown (the listing is cut after the second branch condition). This is not considered to be an important detail.

Point 10: The nature of the transient is seen by inspection of the Type-11 current source connected to node "BUS-M0" . Hian is using the electrical analog for the mechanical system wherein current is torque, and this particular source is the mechanical load, connected to mass number zero. There are two sources in parallel, with the first (value 1.02) representing the steady-state mechanical load. The second one (value -.4) only begins at time TSTART = 20 msec ; this is the transient, a 40% load reduction after just over one cycle of steady-state operation.

So much for documentation and explanation of the input data. On to the solution to this transient problem! Consider the time-step loop variable headings and initial printout:

```
STEP  TIME     BUS-A1       BUS-B1       BUS-C1       BUS-M1       BUS-MO       BUS-A1       BUS-B1       BUS-C1       BUS-M1
                                                                                BUS-A0       BUS-B0       BUS C0       TERRA

               BUS-MO       BUS-MO       UM-1         UM-1         UM-1         UM-1         UM-1         UM-1         UM-1
               TERRA        BUS-M1       TOGEN        OMEGM        THETAE       IRA          IRB          IRC          IS1

               UM-1         UM-1
               IS2          IS3
   0 0.000000 0.136413E+01-0.307450E+00-0.125877E+01 0.100000E+01 0.100030E+01 0.134494E+01-0.957930E+00-0.427010E+00 0.000000E+00
              0.000000E+00 0.101800E+01 0.100124E+01 0.100000E+01 0.937670E+00 0.136400E+01-0.958773E+00-0.427710E+00-0.384800E+01
              .000000E+00 0.000000E+00
   1 0.001000 0.123371E+01 0.317389E+00-0.157099E+01 0.100000E+01 0.100000E+01 0.140030E+01-0.598986E+00-0.891630E+00 0.120946E+01
              0.100003E+01 0.101800E+01 0.997905E+00 0.100000E+01 0.937170E+00 0.140050E+01-0.599866E+00-0.891630E+00-0.322595E+01
              0.387512E-04-0.801940E-02
   2 0.002000 0.743402E+00 0.891584E+00-0.163511E+01 0.100001E+01 0.100001E+01 0.122098E+01 0.108571E-01-0.173161E+01 0.153364E 01
              0.100017E+01 0.101800E+01 0.994567E+00 0.100001E+01 0.937872E+00 0.122098E+01 0.108571E-01-0.123191E+01-0.267361E+01
              0.308536E-03-0.928479E-02
```

Point 11: U.M. output quantities are identified by a pair of A6 names that are internally generated, much as is the case with the production S.M. code. The first name is always "UM-1 " (for the first machine; if there were a 2nd, it would be "UM-2"), while the second identifies the variable in question. Some of these are a little less than obvious, due to requirements of the universal approach. I list all of them in any case:

TOGEN --- electromechanical torque (obvious).

OMEGM --- angular speed ("omega") of the generator, clearly in per unit (note value of unity).

THETAE -- Torque angle ("delta") of the machine, in radians.

IRA ---- Current in the armature winding of phase " " , apparently in per unit here (since the whole electric network is). The "R" is for rotor, documentation of the inverted nature of Hian's U.M. equations. I myself first learned this two days ago! Well, no problem. This is

...es like in the [illegible] generalized machine [illegible] by White and Woodson (the [illegible] formulation was inside out as well, if I still remember my studies during 1965). So, although we continue to talk about the field of a synchronous machine being on the rotor, the user must remember that the U.M. model puts it on the stator (coil "IS1").

IS1 ---- Current in the first stator winding. This is the field circuit, connected to electric network node "BUS-F0", for this synchronous machine problem. Currents "IS2" and "IS3" are in the two remaining stator coils, which are damper windings ("kd" and "kq" in terms of our established S.M. notation, I guess).

Point 12: The machine is clearly coming out of the steady-state very smoothly. The speed and torque look fine. Step 2 shows the beginning of a little wobble: OMEGM = 1.00001 . This grows to 1.00015 by the time we are ready to switch at 20 msec. This has no physical significance, and is in no way to be taken as a possible sign of instability (Hian has run the U.M. in the steady-state for two seconds without any hint of trouble). My own feeling is that the large time-step size of 1.0 msec is explanation enough (since the discretization implies some error).

Well, the simulation was run 1000 time steps, out to the end time of one second. The final two output lines, plus the extrema, follow:

```
900 0.900000 0.164803E+01-0.608536E+00-0.984036E+00 0.996473E+00 0.998990E+00 0.553224E+00-0.751653E+00 0.193449E+00 0.116958E+00
             0.161907E+00 0.518083E+00 0.401135E+00 0.996428E+00 0.455984E+00 0.558224E+00-0.751653E+00 0.193449E+00-0.229072E+01
             0.595779E-01-0.860759E-01
1000 0.100E+01 0.167027E+01-0.566566E+00-0.101915E+01 0.100393E+01 0.100209E+01 0.668745E+00-0.790524E+00 0.121800E+00 0.257324E-01
             0.113804E+00 0.504196E+00 0.470446E+00 0.100353E+01 0.473086E+00 0.466745E+00-0.790524E+00 0.121800E+00-0.229490E+01
             0.763218E-02 0.542550E-01

PEAK OUTPUT VARIABLE VALUES WHICH OCCURRED DURING THE SIMULATION FOLLOW.   A MINUS SIGN MEANS THAT THE PEAK
ABSOLUTE VALUE OCCURRED WITH NEGATIVE POLARITY.   THE ORDER AND COLUMN POSITIONING ARE THE SAME AS FOR THE REGULAR
PRINTED OUTPUT VS. TIME (SEE PRINTED HEADINGS ABOVE).
             0.170030E+01-0.165691E+01 0.149334E+01 0.100779E+01 0.100846E+01 0.141874E+01-0.141540E+01-0.141330E+01-0.292433E+00
            -0.389231E+00 0.101000E+01 0.100344E+01 0.100779E+01 0.340109E+00 0.141878E+01-0.141540E+01-0.141310E+01-0.282600E+01
             0.133334E+00-0.135827E+00
INSTANTS OF TIME AT WHICH THE JUST-PRINTED EXTREMA OCCURRED.
             0.718000E+00 0.443000E+00 0.744000E+00 0.443000E+00 0.312000E+00 0.340000E-01 0.310000E-01 0.200000E-01 0.100000E+00
             0.280000E-01 0.000000E+00 0.480000E-01 0.443000E+00 0.460000E-01 0.340000E-01 0.310000E-01 0.200000E-01 0.000000E+00
             0.179000E+00 0.189000E+00
```

On to plotting. Each time instant was saved (IPLOT=1), and the batch-mode solution involved three printer plots of one variable each (spring torque, field current, torque angle), with 6-inch time axis. These shall not be shown. Instead, the next page is filled with high resolution plots which were made after the fact, using the "COPY" feature (for connection to our Versatek printer/plotter) of interactive plotting (see Vol. IX, 11 May 1979, page PIEP-22). Several comments might be offered about these results:

Point 13: Fig. 1 shows the inductor current, or spring torque, which provides an indication of the relative position of the two rotor masses. Two masses means two eigenvalues (natural frequencies), which are clearly apparent. A quick eyeball inspection shows periods of about 0.6 sec and .14 sec. This can be easily verified theoretically, since poles of the L-C electric network satisfy the Laplace-domain equation S**2 + 1000 = 0 . The roots are the radian

SRFH-8

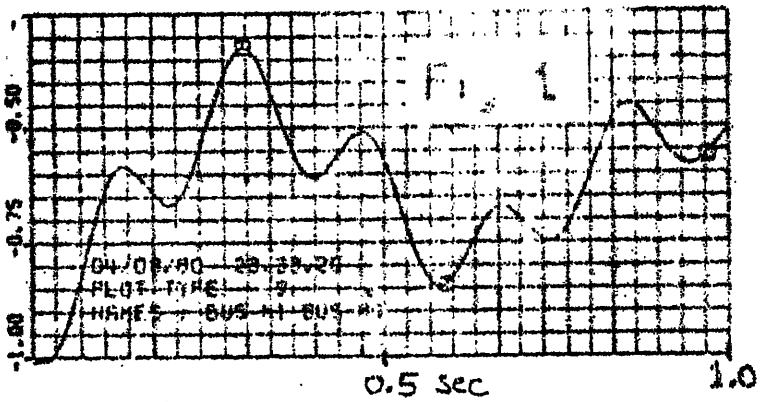


Fig. 1

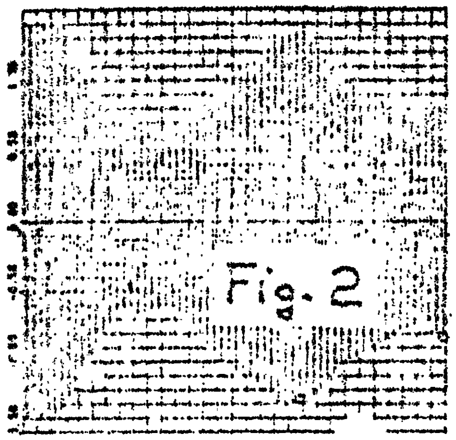


Fig. 2

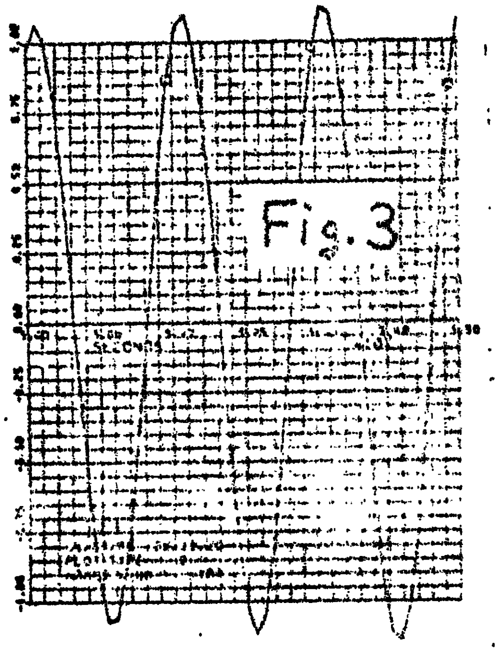


Fig. 3

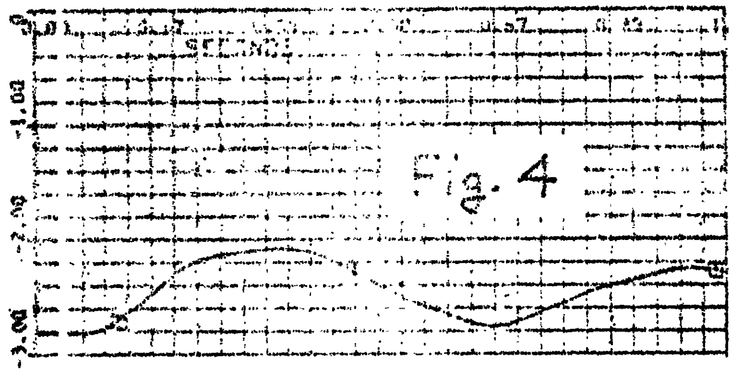


Fig. 4

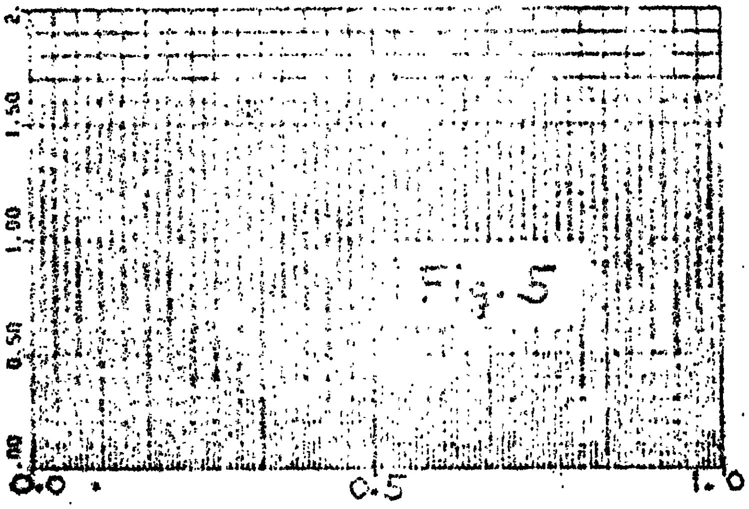


Fig. 5

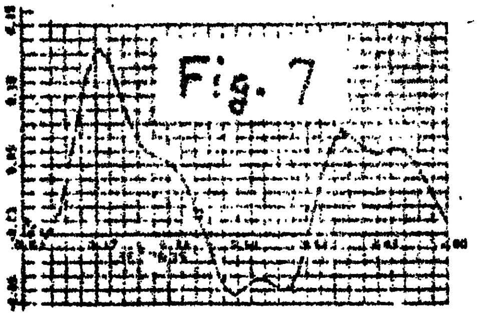


Fig. 7

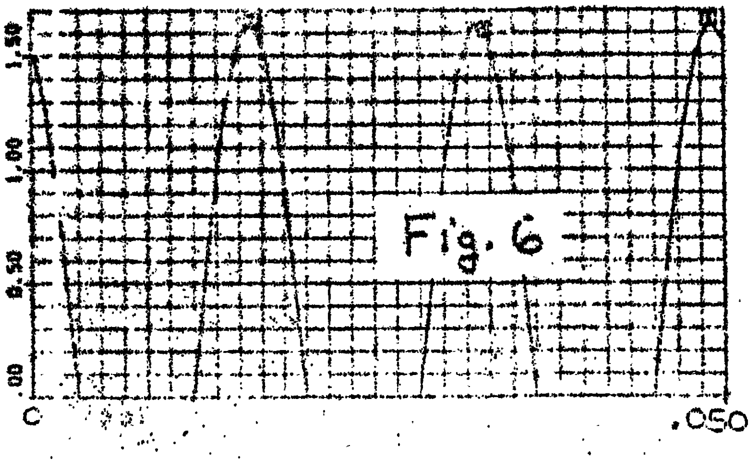


Fig. 6

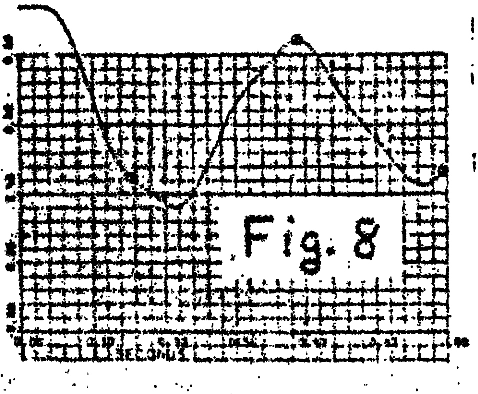


Fig. 8

36m-1

SRFH-9

frequency w = SQRT(1000) , which implies f = 5.033 Hz , and finally a period T = .1987 sec. Is this close enough to be believable? Why the discrepancy? What happened to the second mode, the transient stability mode? I will give Hian an opportunity to interpret this, and provide answers to other questions which I have raised, at the end of the memo.

Point 14: Fig. 2 shows the armature current in phase "a" (UM-1, IRA), over the full simulation interval (0.0, 1.0). The vertical spikes are sixty in number, and in fact sinusoidal. The envelope is being modulated by that slow mode of Point 13 (the transient stability mode, the mode of both U.M. masses swinging together against the infinite bus). That this is indeed sinusoidal (except for the modulation) is seen in Fig. 3, where the time span is (.500, .550), as the envelope is increasing. The discretization due to the 1.0 msec time step is very obvious in such a plot.

Point 15: The field current is shown in Fig. 4; as Hian predicted, the slow mode (transient stability mode) of T = 0.6 seconds is conspicuous here. After the transient dies out, the field current should settle at a reduced value, which is reasonable for a case of load reduction. This is sort of a 2nd order (orthogonal) effect, however, much less pronounced than the adjustment of relative mass positions in Fig. 1.

Point 16: Terminal voltage is shown in Fig. 5. Because of the infinite bus and low-impedance connecting line, it can not change much; and it does not. As with the current in Fig. 3, an expanded display of the first 50 msec shows the expected discretized sine wave (see Fig. 6).

Point 17: Fig. 7 shows current in the direct-axis damper coil (UM-1, IS2). While the transient stability mode dominates, the inter-mass ringing is also clearly present.

Point 18: Finally, in Fig. 8, we have the torque angle (UM-1, THETAE). As expected, the oscillation corresponds to the transient stability mode (indeed, it is almost the definition of it). But is there some weak inter-mass ringing in there too? Oh where is that spectral analyzer which everyone talks about!

(III) DIRECTION OF FUTURE U.M. WORK; HIAN'S COMMENTS

Well, that is about all the explanation that I intend to offer. Possibly there might be another example at some time in the future, but no promises are being made. By now readers should have a reasonable idea of what is involved, which is all I intended to convey.

So, Hian continues with the testing, with the 3-phase induction machine now of top priority. We are now negotiating with Ned and his industrial client in Minneapolis, to see if they could be interested in volunteering as guinea pigs. They have a production problem involving a 3-phase induction motor, about which they already know quite a bit. The EMTP would be used to improve the modeling (e.g., Ned's suggestion to put frequency dependence into the rotor circuit). But Ned is very busy, and the logistics of communicating EMTP competence to the client are a problem. We at BPA can not so get involved, though I do want such a production user to rapidly stress Hian's code! We'll see.

36m-2

SRFH-10

Hian will be writing user instructions, and these shall form Section 1.63 of the new EMTP Reference Manual (the old User's Manual) that is now being worked on. With luck, the advance copies for Madison should have this material as an integral part.

Oh, I forgot something! running time! The case summary statistics for the solution of Section II show 29.500 for CP SEC spent in the time-step loop. Not bad at all, for 1000 steps! To get a feel for how much of this we can blame on Hian, I took a similar problem involving Vladimir's Type-59 machine. The machine itself came from minicomputer benchmark DC-23 without alteration. This only has a single mass, so is slightly more simple than Hian's. As for the network, I used series uncoupled inductors of 150 ohms to tie the machine to an infinite bus of Va = 11.2 THETA = -15 degrees . There was no transient, just a smooth continuation of 1000 steps out to 200 msec. The printout and plotting intervals were the same as Hian's problem, too. The operating point should have been reasonable, for it was close to Vladimir's ("M21," printout of initial condition torque was .3823E-6, while I got .3542E-6 for the doctored problem). So, Vladimir has a slightly simpler network, no transient, and smaller time step (.2 msec vs. 1.0 msec). What was his solution time? 11.600 sec in the time-step loop. Although this is all extremely incomplete and premature, Hian nevertheless comes off with flying colors on the first comparison. Based on Vladimir's previous rule of thumb that his code is two or three times as fast as the Type-50 (SCE) model, it looks like Hian's computational efficiency for this problem is comparable to that for the Type-50 (SCE) code. Amazing! I am impressed, and very happy (though only production testing under a variety of circumstances will allow a general conclusion)!

So much for WSM's commentary. I want to give Hian a chance to pass along whatever occurs to him. The rest of the section is his!

The purpose of this note is to clarify the questions as posed in Scott's memorandum. No attempt will be made to present a complete documentation of the U.M. Rather I would like to lean on Scott's excellent account of the current U.M. facilities and supply the following points which I hope will complement this first information flow of the U.M.

(a) The machine types which can be represented are:

Type 1: Synchr. Mach., 3-phase power side
Type 2: Synchr. Mach., 2-phase power side
Type 3: Ind. Mach., 3-phase power side
Type 4: Ind. Mach., 3-phase power side, 3-phase excitation side
Type 5: Ind. Mach., 2-phase power side
Type 6: Single-phase A.C. machines, induction or synchronous, 1-phase excitation
Type 7: Same as type 6, except for 2-phase excitation
Type 8: D.C. Machine, separately excited
Type 9: D.C. Machine, series compound (long shunt) field
Type 10: D.C. Machine, series field
Type 11: D.C. Machine, parallel compound (short shunt) field
Type 12: D.C. Machine, parallel field

(b) Number of machines and coils, compensation:

The number of U.M. machines which can be used is arbitrary. For each machine the following rules apply. The maximum number of coils on the power side is restricted to three. This is obviously justified by our today's usage of electric machines. These 3 coils are 3-phase compensated, i.e., they can be externally connected to each other in one

36m-3

electrical network. Except for U.M. type 4, 6 and 7, all machine types can have an arbitrary number of d- and q-axis excitation coils. As far as compensation of the excitation coils is concerned, the general rule here is that only the first 3 excitation coils are 3-phase compensated. i.e., only the first 3 excitation coils are permitted to be externally connected to each other in one single electric network. If in addition more excitation coils are used, then each of these coils must be totally disconnected from other coils used.

(Note: Therefore, the 3-phase excitation side of U.M. type 4 is also 3-phase compensated, which makes U.M. type 4 suitable for speed control through sliprings connected to a 3-phase rectifier/inverter bridge or external resistances.)

(c) Saturation:

User has the option of implementing a d-axis, a q-axis or both d- and q-axis saturation non-linearity. The actual saturation curve is to be approximated by a two straight-line segment curve at this moment.

(d) Initialization:

Automatic initialization is not available yet. Until this feature is implemented, the U.M. requires initialization of all coil currents and coil terminal voltages. For the mechanical side the initialization of the mechanical speed and rotor position angle (or torque angle for synchronous machines) is needed.

(e) Output labeling:

Learning about Scott's confusion with the interpretation of the coil current output (as described in point 11 of Scott's memo), the coil currents labeling is now changed into:

IPA current of the a-phase coil on the power side of the machine (likewise IPB for phase b and IPC for phase c)
IE1 current of coil number 1 on the excitation side of the machine (likewise IE2 for coil number 2, etc.)

With this change, the user need not to bother about the internal stator and rotor coil arrangement of the U.M. The power and excitation side of any machine type is always fixed and unambiguous to the user. Exception to this agreement will be the simple-phase A.C. machines, as will be explained later in a full documentation of the U.M.

(f) Per Unit option:

The user has the option to use the SI units (i.e. A, V, W, sec, N.m, m, etc.) for the U.M. variables or the per unit quantities as treated by Fouad and Anderson (their book: "Power System Control and Stability, Iowa State University Press, 1977, pp 92-98, pp 414-418).

(g) Ad point 13 of Scott's memo:

Scott observed two modes in his test-run of subjecting a 2-mass synchronous generator to a step-change of the external mechanical torque. The first mode observed is correctly attributed to the pure mechanical energy swings. The questioned second mode is to be explained as stemming from the electromechanical energy interaction, which is proportional to the ratio of the synchronizing torque and the generator rotor moment of inertia. This is usually in the order of 1 sec. Scott's approximated verification of the first mode is quite close, considering the fact that the system has 14 eigenvalues.

1.7 CARDS FOR OVERRIDING INITIAL CONDITIONS

These cards are used only if the user wants to supply initial conditions himself. The transients program starts from correct initial conditions as long as everything was zero at $t<0$ or if an ac steady-state existed at $t<0$ (the latter is simply indicated by TSTART<0 on sinusoidal source cards)

Initial conditions that are neither zero nor ac steady-state must be supplied as input. Any initial conditions that are provided through input will override the respective zero-or ac-steady-state initial conditions computed by the program. There are two cases where the user might want to supply the initial conditions:

a) Continuation of a previously run case, where a continuation beyond t_{max} was already contemplated. The continuation can either use the same Δt or a changed Δt. Continuation is handled by having the preceding run punch the voltages and currents at the very last step (see section 1.1). Then simply use this data deck' in the new run (no blank card at end!). Note that continuation works only if

   (1) the passive network has not been changed between the previous and the new run, including the order in which the branch cards are read in, and

   (2) there are no branches with distributed parameters (in this case the punching in the previous run would have been interrupted; see section 1.1).

b) New Case: If the user knows the initial conditions for a new case, he can supply them as part of the input. This could be used to start a case from steady-state conditions with more frequencies than the fundamental (example: steady-state performance with a number of super-imposed harmonic sources); however, the user has to find the initial conditions himself (an extension of the automatic ac steady-state solution to the case of super-imposed sinusoidal sources with differing frequencies is planned). Note that zero initial conditions or ac steady-state conditions at only one frequency are automatically handled by the program.*)

   Trap charge: Supply all voltage values at nodes with trap charge (steady state frequency = 0 or blank on very first voltage card). Supply cards for currents in linear branches having trap charges (only node names must be listed and fields A, B, C, D are left blank if initial currents are zero).

a) RULES:

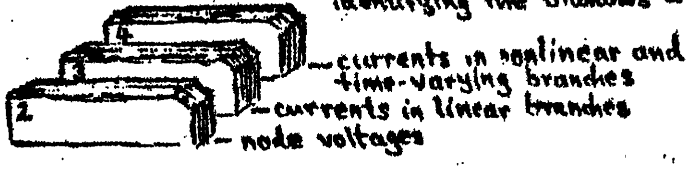
   (1) In networks containing branches with distributed parameters, only dc or ac-steady-state solutions can be used as initial conditions. In this case, all initial voltages and currents must be specified as phasor values $x(0)+jy(0)$, where $x(0)$ is the instantaneous value at $t=0$ (note that the magnitude of the phasor quantity is the crest value and not the rms value). Punch the steady-state frequency into the very first card with an initial node voltage on it.

---

*) It is advisable to let the program determine initial conditions whenever possible, that is for ac steady-state as well as for dc steady-state. In the latter case, use cosine functions with very low frequency to simulate dc sources. f = 0.001 Hz worked very well in studies on the HVDC Pacific Intertie.

(2) In networks without distributed parameters, any initial conditions are acceptable. In this case, all initial voltages and currents are specified as instantaneous values x(0) (ignore format fields provided for the imaginary part y(0) of phasor values and the steady-state frequency as described in rule 1).

(3) Stack cards for initial conditions in the following order: Cards for node voltages ("2" in column 2), then cards for currents in linear branches ("3" in column 2), and finally cards for currents in nonlinear and time-varying branches ("4" in column 2). This order is mandatory, since the program computes initial conditions in a branch from the currents on the card plus the node voltages already read in. If cards for node voltages were read in behind cards for branch currents, then the program would assume voltages zero at both ends of the branch. If there are parallel branches with identical node pairs, then all initial conditions on the "3"-cards go into one branch only, namely into the first one encountered in the branch list. In general, this produces wrong initial conditions (please contact the Methods Analysis Unit if this problem comes up. If there are only 2 branches in parallel, then the problem can be avoided by identifying the branches with the node pairs in reverse order, say 1st branch "R to L" and 2nd branch "L to R". This makes the 2 branches distinguishable for the "3"-cards).



4
3
2
currents in nonlinear and time-varying branches
currents in linear branches
node voltages

b) FORMAT:

(1) Card for node voltages ("2" in column 2):

	1 2	3 4 5 6 7 8	9 10 11 12 13 14 15 16 17 18 19 20 21 22 23	24 25 26 27 28 29 30 31 32 33 34 35 36 37 38	39 40 41 42 43 44 45 46 47 48 49 50 51 52 53
	IDENTIFICATION	NODE NAME	Re{E(0)} or e(0)	Im{E(0)}	f in HZ on first card in this stack of node voltage cards
FORMAT:	2	A6	E15.8	E15.8	E 15.8

f = steady-state frequency (punch only on very first card, and only in cases where branches with distributed parameters are present)

Re{E(0)} + j Im{E(0)} = phasor voltage at t = 0 (rule 1)
e(0) = instantaneous voltage at t = 0 (rule 2)

(2) Card for linear branch currents ("3" in column 2):

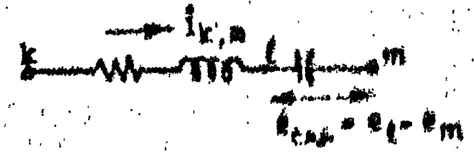
	1-2	3-8	9-14	15-29	30-44	45-59	60-74
	[illegible]	1st NODE k	2nd NODE m	A	B	C	D
Format:	3	A6	A6	E15.8	E15.8	E15.8	E 15.8

Sequence of node names on this card and on associated branch card (section 1.2) must be identical (example: if branch card says "L" to "R", then punch "L" to "R" and not "R" to "L").

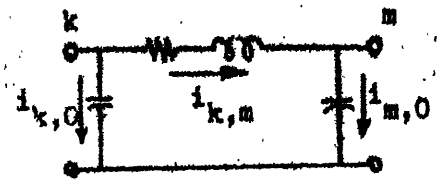
a) Lumped series R-L-C: No card necessary if branch is purely resistive (L = 0, $\frac{1}{\omega C}$ = 0) or if current through branch plus [illegible] capacitor voltage are both zero; otherwise punch

$i_{k,m}(0)$ in A

$e_{CAP}(0)$ in B



b) Single or multiphase π-equivalent:



Note: Data-input listing interpretation of the 1st distributed-parameter line card reads "LINEAR I." ; interpretation on the 2nd and later such cards of a multi-phase line reads "DISTRIB. I." .

Punch $i_{k,m}(0)$ in A

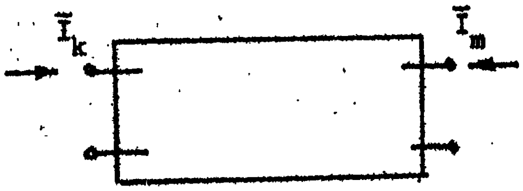
$i_{k,o}(0)$ in B

$i_{m,o}(0)$ in C

This card must be punched in case of non-zero terminal voltages, even if all currents are zero; otherwise all initial conditions in the circuit, including charges on the capacitors, will be set to zero.

For multiphase π-equivalents, punch a card for each phase in same phase sequence as branch cards were read in. Here, $i_{k,o}$ is the total shunt current going to ground and the other phases.

c) Single or multiphase line with distributed L', C':



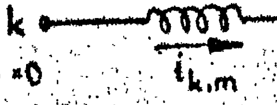
Punch: $\mathrm{Re}(\bar{I}_k)$ in A
$\mathrm{Im}(\bar{I}_k)$ in B
$\mathrm{Re}(\bar{I}_m)$ in C
$\mathrm{Im}(\bar{I}_m)$ in D

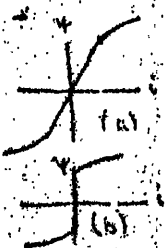
See rule 1 why phasor values must be given. This card must be punched in case of non-zero terminal voltages, even if all currents are zero. For multiphase lines, punch a card for each phase in same sequence as branch cards were read in.

(3) Card for nonlinear and time varying branch currents ("4" in column 2):

1 2	3 4 5 6 7 8	9 10 11 12 13 14	15 16 17 18 19 20 21 22 23 24 25 26 27 28 29	30 31 32 33 34 35 36 37 38 39 40 41 42 43 44
IDENT.	1st NODE k	2nd NODE m	$i_{k,m}$ in units of current	$\psi_{k,m}$ in (units of voltage)·S
4				
Format:	A6	A6	E15.8	E15.8

Leave $\psi_{k,m}$ blank and supply $i_{k,m}$ only as long as $\psi_{k,m}$ can be obtained from the nonlinear characteristic (see Fig. a). Supply $\psi_{k,m}$ if $i_{k,m}(0)=0$ and characteristic has infinite slope at $i=0$ (see Fig. b).





Incomplete initial-condition specification capability (WARNING)

Unfortunately, the manual specification of initial conditions (as per Section 1.7) is not possible at the present time for many EMTP components. Specifically excluded are the following components:

a) Saturable "TRANSFORMER" component of Section 1.25 ;

b) Recursive convolution frequency-dependent line modeling of Section 1.27 . Well, actually, sinusoidal initial conditions (past history) is possible, for those who know how. But the format shall not be explained here.

c) Type-99 pseudo-nonlinear resistance of Section 1.28 ;

d) Type-98 pseudo-nonlinear reactor of Section 1.29 ;

e) Type-97 staircase resistance of Section 1.30 ;

f) Type-94 SiC surge arrester of Section 1.34 ;

g) Type-16 controlled dc voltage source of Section 1.61 ;

h) Dynamic synchronous machine (S.M.) components of Section 1.62 ;

i) TACS modeling (see Section 8.4 for TACS own steady-state initialization rules)

Hence, for typical, modern procuction studies, the manual specification (override) of initial conditions is not possible. This is as of May, 1980 ("M27." idents).

As for the future, plans are to expand the initial condition input capability so as to handle all possible EMTP components under all possible conditions. Yet, it is not expected that the user will actually punch such initial condition cards himself, manually. For one thing, the operation is tricky and error prone at best, based on BPA experience; for large cases, it is extremely tedious; and for non-sinusoidal past history of distributed components or delay lines, the data is voluminous and impossible to calculate by hand anyway. So, such initial condition cards will be punched by the EMTP itself, as terminal conditions of a simulation which has been stopped by the user. This capability is seen to be a crucial ingredient of a real-time EMTP simulator package, which will be fully interactive. Stay tuned!

1.8 OUTPUT-VARIABLE SPECIFICATION CARDS

The time response of the electric network being solved is available for the user's inspection via any of the four procedures which follow:

Output type 1 :	Tabulated decimal numbers, from the line printer.
Output type 2 :	Graphs produced on the line printer (so-called "printer plotting" of the solution).
Output type 3 :	Pen and ink graphs, produced by the Calcomp x-y plotter.
Output type 4 :	Graphs drawn on a CRT screen (and preserved permanently by means of an attached hard-copy unit), according to commands which are issued interactively by the user.

Output types 1 and 2 are of course available to every user of interest, since they require only a 132-column line printer. Output type 3 can be utilized only by those having a pen-and-ink plotter which can be controlled through Calcomp subroutine calls. Finally, output type 4 is available only on systems having a CRT terminal with vector-graphics capability, and for which the appropriate special interactive CRT plotting program has been written. As of December 1975, output type 4 has been activated only for a CDC computer and Tektronix CRT terminal, as in operation at BPA in Portland, Oregon (see Ref. 8, January 25, 1975).

In any case, the user can only look at variables for which output requests have been made as part of the data case. The procedure for doing this depends upon whether a conventional single deterministic simulation is involved, or on the contrary, a statistical overvoltage study:

1.8a Output-Variable Specification for Conventional Data Cases

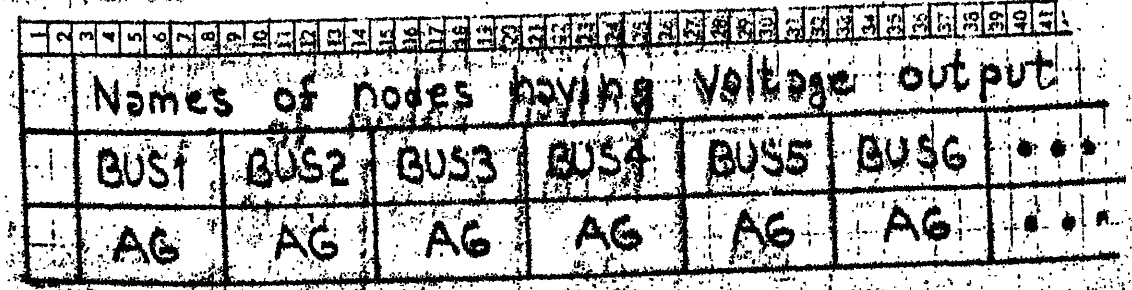
Variable values for voltages, currents, powers, and/or energies are computed by the EMTP at discrete time instants $t = 0$, Δt , $2\Delta t$, etc. Such values are then either printed (with frequency controlled by miscellaneous data parameter "IOUT" ; see Section 1.0h), or they are written to disk via logical unit number 4 with frequency "IPLOT" (miscellaneous data parameter; see Section 1.0h), for purposes of later plotting after the simulation is finished. In any case, any variables to so be outputed must be specified by the user, as follows:

Node voltage output

As per Point a-7 of Section 1.[illegible], the user must input one or more cards specifying all node names for which he will print or plot the node voltages (voltage to ground).

a) All node voltages desired: Punch a single output specification card, with just a "1" in column 2 ; do not terminate with a blank card.

b) Selective node-voltage output: List the node names on one or more cards which have columns 1-2 blank, with at least the first field (variable BUS1 , read from columns 3-8) non-blank. Terminate such cards by a blank card.



Note that of the 13 potential fields per card, only the first must always be non-blank (except for the terminating blank card, of course); otherwise fields can randomly be left blank, and will be passed over. For example, the following three cards request node-voltage output for the six nodes named ALPHA, BETA, GAMMA, DELTA, PSI, AND ZETA.

```
| ALPHA |      BETA  |
| GAMMA |            |
| DELTA |PSI         |ZETA
 Blank Card
```

c) <u>No node voltages desired:</u> Supply but a single blank card (which is taken as the blank card ending the non-existant selective node-voltage specification cards).

<u>Branch output:</u>

Branches and/or switches which are to have output were flagged by column-80 punches as the branch cards were inputted; hence no further specification is required at this point.

The printed heading for branch-variable output consists of pairs of node names, one above the other. This ordering (upper to lower) indicates the polarity of the output. Suppose that node k represents the upper node of the pair, and node m the lower one; then:

BUS K
BUS M

Sample heading

a) Branch voltage output is $v_{km}(t) = v_k(t) - v_m(t)$

b) Branch current output is $i_{km}(t)$, the flow from node k to node m.

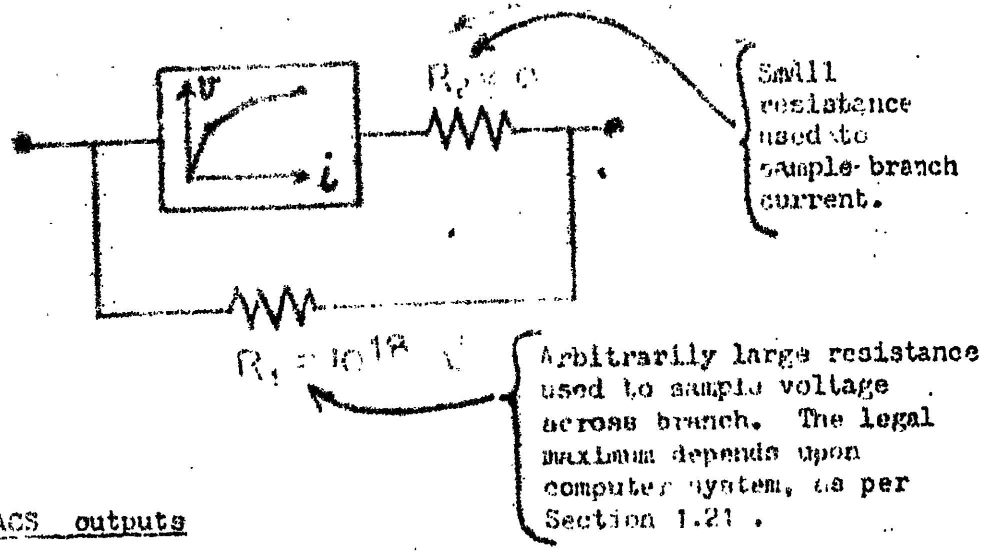
For non-switch elements, power and energy which are outputted represent the consumption (loss or storage) of the branch, the net flow into the branch from time zero (t=0) up to the time in question. For switches, the power and energy are flows through the switch:

c) Switch power output is $P_{km}(t) = P_k(t) - P_m(t) \approx v_k(t) \cdot i_{km}(t)$

d) Switch energy output is $E_{km}(t) = \int_0^t P_{km}(\xi)\, d\xi$.

All ~~branch~~ branch outputs should always be correct, except possibly at time zero (t=0), where switches will generally have erroneous current and power. Flashing likewise creates no problems, unless output for parallel branches should be requested. Then as per rule 3 of Section 1.10, only the first current (energy) output of the two in parallel is accessible to the user at the present time.

As a practical restriction, the above limitation is not serious. One can always insert a near-zero-resistance branch, thereby eliminating any parallel connection. For example, should power P(t) and energy E(t) be desired for a nonlinear resistance in addition to the branch current and voltage, then the configuration shown below could be used. Resistance R_2 is chosen to be "small," in accord with the rule concerning system-dependent minimum values (see Section 1.21). Current output (a 1-punch in column 80) is requested on the branch card for resistance R_2. Resistance R_1 is chosen to be very large, and branch voltage output is to be requested for it (a 2-punch in column 80). The nonlinear element has a 4-punch in column 80 to give its power and energy consumption.



Small resistance used to sample branch current.

Arbitrarily large resistance used to sample voltage across branch. The legal maximum depends upon computer system, as per Section 1.21 .

Synchronous machine and TACS outputs

In all, there are five general groupings of output variables for EMTP printed output of the time-step loop. The just-described node voltages come first, then branch voltages are second, and branch currents come third. Then come two additional classes of EMTP output variables: synchronous machine output variables follow as a fourth grouping, and TACS output quantities represent a fifth and final grouping.

Output requests for synchronous machine variables are part of the synchronous machine input data (see Section 1.62 for the details). Variables are identified by a pair of 6-character alphanumeric identifying names for each quantity; these are generated internally, as explained in the just-cited reference. For plotting purposes, the user treats synchronous machine variables as though they were branch currents, though (using a "9" in column 3 of batch-mode plot cards).

A comparable statement to that just made for synchronous machines could also be made for the universal machine (U.M.) of Section 1.63 .

Output requests for TACS variables are part of the TACS input data which immediately follows the EMTP miscellaneous data cards and their extensions. See Section 8.[illegible] for details. One 6-character alphanumeric name identifies the desired TACS variable, of course. But a pair of names is required for the variable identification, with the TACS name being the second name of the pair. The first name "TACS " is automatically supplied internally by the EMTP. For example, "TIMEX " is the name of the built-in variable which carries the current simulation time; for output purposes, the pair of names "TACS " and "TIMEX " would be used, then. For plotting purposes, the user treats TACS variables as though they were branch currents (using a "9" in column 3 of batch-mode plot cards).

The following sample of EMTP line printer output for the beginning of the time-step loop illustrates the five classes of output variables just described. Since there was no TACS representation, the fifth class or grouping is empty, note:

```
 OF BUS NAMES FOR NODE-VOLTAGE OUTPUT.      1  NAVH ANAVH BNAVH C
IK GA O ENDING NODE NAMES FOR VOLTAGE OUTPUT.  1

IMN HEADINGS FOR THE  16  EMTP OUTPUT VARIABLES FOLLOW.   THESE ARE ORDERED ACCORDING TO THE FIVE
IBLE EMTP OUTPUT-VARIABLE CLASSES, AS FOLLOWS ....
RST    3  OUTPUT VARIABLES ARE ELECTRIC-NETWORK NODE VOLTAGES (WITH RESPECT TO LOCAL GROUND).
IEXT   1  OUTPUT VARIABLES ARE BRANCH VOLTAGES (VOLTAGE OF UPPER NODE MINUS VOLTAGE OF LOWER NODE).
IEXT   3  OUTPUT VARIABLES ARE BRANCH CURRENTS (FLOWING FROM THE UPPER EMTP NODE TO THE LOWER).
IEXT   9  OUTPUT VARIABLES PERTAIN TO DYNAMIC SYNCHRONOUS MACHINES, WITH NAMES GENERATED INTERNALLY.
INAL   0  OUTPUT VARIABLES BELONG TO  'TACS'  (NOTE. INTERNALLY-ADDED UPPER NAME OF PAIR).
ICH  POWER  CONSUMPTION (POWER  FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH VOLTAGE FOR THIS GROUPING.
ICH  ENERGY CONSUMPTION (ENERGY FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH CURRENT FOR THIS GROUPING.

EP      TIME      NAVH A      NAVH B      NAVH C      MCC1 A      MCC1 B      MCC1 C      GEN  A      GEN  B      GEN
                                                      MCC2 A      MCC2 B      MCC2 C      NAVL A      NAVL B      NAVL

                  MACH 1      MACH 1      MACH 1      MACH 1      MACH 1      MACH 1      MACH 1
                  TQ GEN      VEL 5       TQS 12      TQS 23      TQS 34      TQS 45      TQS 56
                                                        SWITCH 'GEN  A' TO 'NAVL A' CLOSED AFTER -.10000E+01 SE
                                                        SWITCH 'GEN  B' TO 'NAVL B' CLOSED AFTER -.10000E+01 SE
                                                        SWITCH 'GEN  C' TO 'NAVL C' CLOSED AFTER -.10000E+01 SE
                                                        SWITCH 'SHT  A' TO '      ' CLOSED AFTER -.0          SE
                                                        SWITCH 'SHT  B' TO '      ' CLOSED AFTER -.0          SE
                                                        SWITCH 'SHT  C' TO '      ' CLOSED AFTER -.0          SE
0  -.000000  .541213E+05 -.384960E+06  .339847E+06  .160343E+06  .106311E+06  .318438E+05  .0          .0          .0
             .900010E+00  .0           .270885E+00  .986692E+00  .704301E+00  .982958E+00  .294099E-02
```

1.8b Output-Variable Specification for "STATISTICS" or "SYSTEMATIC" Data Case

General Introduction

A "STATISTICS" or "SYSTEMATIC" overvoltage study is distinct from all other EMTP data cases in that multiple simulations are automatically generated internally by the EMTP. Integer miscellaneous data parameter "NENERG" (see Section 1.0h) defines the number of energizations which are to be simulated. Each energization gives a different solution, due to differences in the closing times for "STATISTICS" or "SYSTEMATIC" switches (see Section 1.40, Class 3A or 3B switch cards). For each energization, only the vector of variable maxima is available for printing, and a statistical tabulation of all |NENERG| such vectors is automatically provided at the conclusion of all such internally-generated simulations. This is the statistical overvoltage output —— line printer output which occurs for either "STATISTICS" or "SYSTEMATIC" data cases. There is no associated plotting (unlike conventional cases, where printing and plotting go together). It is the purpose of the present section to explain how the user requests such overvoltage output, and what the printout looks like.

But before describing the output specification cards for the statistical overvoltage tabulation, it should be mentioned that there also is a base-case solution which precedes the |NENERG| energizations. For a "STATISTICS" data case, this is a zero-th energization which is made with all variances temporarily set to zero. For a "SYSTEMATIC" data case, either all beginning or all mid-closing times of the switches are used —— whichever the user has chosen to input (see Section 1.40, Class 3B switch cards). Before appending the requests for statistical overvoltage tabulations, the user must complete the data deck for the base case, pretending that it is a separate conventional simulation. The overall (total) data structure thus has the following components and ordering:

- EMTP source cards, terminated by a blank card.
- Node-voltage output specification card or cards, applicable only to the base case. See the beginning of the present section for an explanation of the format. If node voltages are selectively requested, this data will be terminated by a blank card.
- Batch-mode plot-specification cards, applicable to the base-case solution only. These are terminated by a blank card.
- Output-specification cards for purposes of statistical overvoltage tabulation, terminated by a blank card.

It now only remains for us to describe the final of these items.

Any column-80 output-request punches on branch or switch cards apply only to the base-case solution; such requests are disregarded for the statistical overvoltage tabulation. Once the base-case solution is completed, an all-new output vector is formed, to be used for the |NENERG| energizations the solutions of which will be processed statistically. Only voltage outputs ---- both node (to ground), and the difference of two node voltages ---- are permitted for this purpose. All such output quantities must be specified explicitely, variable by variable along with an appropriate per unit base voltage, as outlined below.

Output variables for the |NENERG| energizations of a "STATISTICS" or "SYSTEMATIC" data case are all specified on cards which are to be punched as follows:

IBROPT	Base Voltage	Network node names for output specification										
	BASEV	BUS1	BUS2	BUS3	BUS4	BUS5	BUS6	BUS7	BUS8	BUS9	BUS10	BUS11
I2	E12.0	A6	A6	A6	A6	A6	A6	A6	A6	A6	A6	A6

IBROPT ------ Type code for this output-specification card, telling the type of voltages in question:

- 0 ⇒ This card is for node-voltage specifications.
- -1 ⇒ This card is for voltage-difference (e.g., branch voltage) specifications.

BASEV ------ Base voltage, in units of voltage for the data case, which is to be used for the per unit statistical tabulation of all variables which are specified on this data card.

A blank or zero punch is given a default value equal to the voltage which the EMTP read from the user's first source card, assuming it was a type-14 sinusoidal voltage source. See Section 1.[illegible] , field "AMPLITUDE" of columns 11-20 of the source card.

BUS1
BUS2
•
•
•
BUS10
BUS11 ------ Node names of the user's network, each A6 alphanumeric information, which specify the desired output variables for the statistical overvoltage study. There are two distinct cases, depending on the value of "IBROPT".

a) If IBROPT = 0 , the variables in question are node names which are to have node-voltage (to ground) output. Blank fields are ignored.

b) If IBROPT = -1 , taken in pairs the variables in question are the node names which specify the voltage differences which are desired as output quantities. There need not be any actual branch in the user's network which connects these two nodes, note, so one is not restricted just to actual branch voltages. The final field "BUS11" is totally ignored, since the specification of node pairs takes an even number of fields. A pair of two blank fields is ignored.

There are no ordering restrictions on such "STATISTICS" output-specification cards, among themselves. Their end is signaled to the EMTP by a blank card. Statistical overvoltage tabulations for output variables will occur in the order that the specifications are encountered on these input cards.

Illustrative example of data input

```
      303000. JDAYA       JDAYB
      303000.       JDAYC
-1     14450.             SWA   TA
              LUMPY
 Blank Card
```

Here node-voltage outputs have been requested for nodes "JDAYA " , "JDAYB " , "JDAYC " , and "LUMPY " , with the first three on a per unit base of 303,000 volts, and with "LUMPY" on a base of whatever the first source card voltage happens to be. There also will be output for the voltage difference from "SWA " to "TA " , on a base of 14,450 volts ----- which might typically be a transient recovery voltage across an open breaker which connects a generator to its step-up transformer.

Explanation of "STATISTICS" printed output

The EMTP printed outputs which are available to the architect of a statistical overvoltage study include the following:

Output a : Switch closing times for each energization.

Printout of the switch closing times T_{close} is automatically provided if the user punches the statistics miscellaneous data variable "ISW" equal to unity. See Section 1.1a .

Output b : Maximum voltages of each energization.

Printout of the vector of maximum variable values for each energization is automatically provided. This is comparable to what the user gets by setting miscellaneous data pa "MAXOUT" (see Section 1.0h) equal to unity for a convention deterministic simulation. The "reference angle" (see Section 1.40, Class 3) is also automatically provided, as part of this printout.

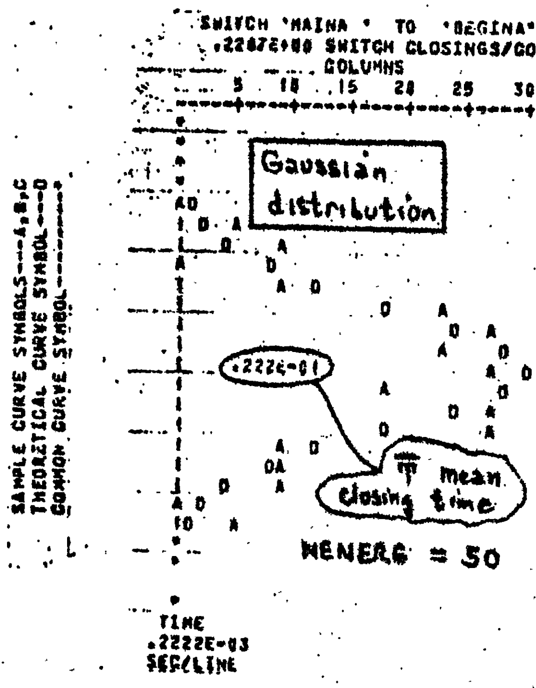
Output c : **Statistical distribution of voltages**

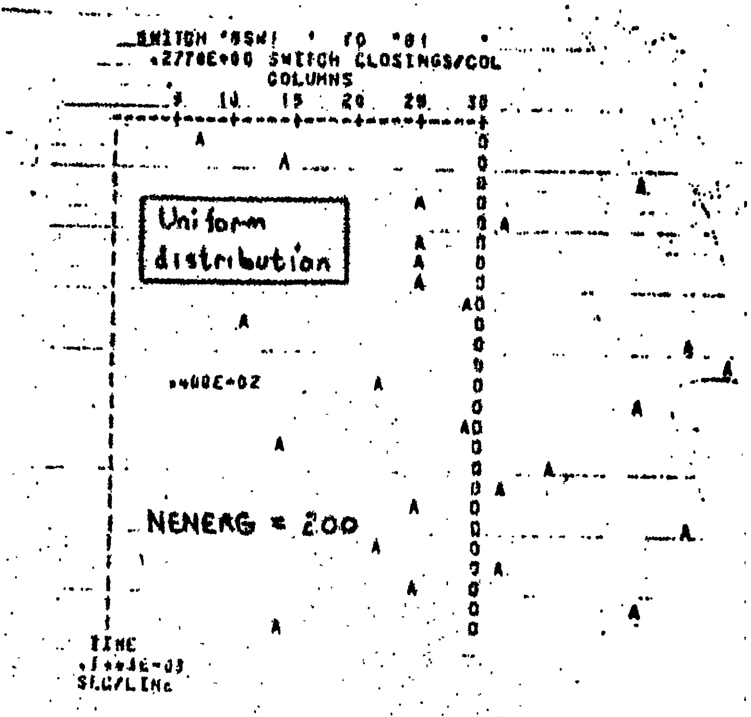
Statistical distributions of maximum output-variable values are automatically provided. These are both one at a time, and also as part of the distribution for the union of all such individual outputs which have the same base voltage.

Output d : **Mini lineprinter plots of switch closing times**

For "STATISTICS" data cases only, the end of the statistical tabulation of overvoltage output is signaled by line printer plots of the switch closing times. Each "STATISTICS" switch has such a mini plot, the size of which is always the same : 30 columns wide by 25 lines (of the printer) long. Up to three such plots can be spaced horizontally across the page. Experimental (sample) values are marked by the symbol "A" for the left-hand plot, "B" for the center plot (if any), and "C" for the right-hand plot (if any). The symbol "D" is used for all theoretical distributions (which will be either bell-shaped or vertical straight lines). The order of output of these plots is the same as the order of switch card input. More than one plot is produced horizontally on the page if the following one or two switches have identically the same variance as the first one (which goes on the left). This will normally be the situation for the poles of a 3-phase breaker, and the user will generally want all three graphs to be spaced horizontally across the page. If the user wants otherwise, he can slightly perturb one or more variances (a switch with a variance which differs from the preceding one will be placed below on the left, automatically).

Two illustrations of the printer plots of "Output d" are shown immediately below. Although spaced horizontally, the reader may note that they were not actually printed this way by the computer (since both use the symbol "A").

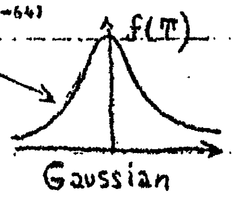




An illustrative sample of "Output a" and "Output b" for a small statistical overvoltage study appears as follows:

```
DATA CASE NOW READY TO BE SOLVED IS A STATISTICAL OVERVOLTAGE STUDY WHICH INVOLVES   3 ENERGIZATIONS
RAMETER  'NENERG' OF COLUMNS 65-72 OF THE 2ND MISC. DATA CARD).   CLOSING TIMES FOR THE SPECIALLY-FLAGGED
ICHES (WITH  'STATISTICS'  PUNCHED IN COLUMNS 55-64) ARE VARIED RANDOMLY, ACCORDING TO A NORMAL  DISTRIBUTION.
USER CAN SELECT EITHER UNIFORM OR NORMAL DISTRIBUTIONS, BASED ON THE VALUE OF PARAMETER  'IDIST'  OF COLUMNS
   OF THE SPECIAL STATISTICS MISC. DATA CARD.   THE FOLLOWING IS A LISTING OF SWITCHES WHOSE CLOSING TIMES ARE
 STATISTICALLY VARIED, ALONG WITH THE ASSOCIATED MEAN AND STANDARD DEVIATION FOR THE DISTRIBUTION, AS REQUESTED
HE USER.
  ENTRY     SWITCH       FROM          TO        SWITCH CLOSING TIME  'TCLOSE'  IN SEC
  NUMBER    NUMBER        BUS          BUS              MEAN (SEC)       STD. DEVIATION
     1           1      ASW1.      A1                .032000             .000100
     2           2      BSW1       B1                .04000              .001000
     3           3      CSW1       C1                .05000              .001000
IN ADDITION TO SWITCH-TIME VARIATION CAUSED BY EACH SWITCH'S OWN DISTRIBUTION, THERE IS THE ADDED RANDOM
AY WHICH IS THE SAME FOR ALL SWITCHES, REFERED TO BY THE TERM 'REFERENCE ANGLE'.   DISTRIBUTION FOR THIS
AY IS UNIFORM OVER THE TIME INTERVAL FROM   -.0          TO    .36000E+03 DEGREES BASED ON     .600E+02 HZ
QUENCY.   THIS WAS ALL SPECIFIED BY THE USER USING FIELD:  'DEGMIN' ,  'DEGMAX' ,  AND  'STATFR'  (COLS. 41-64)
THE SPECIAL STATISTICS MISC. DATA CARD.
EVER, IF THE PARAMETER 'ITEST' (FOUND IN COL. 9-16 OF THE STATISTICS MISC. DATA CARD) IS GREATER THAN ZERO,
 REFERENCE ANGLE IS SET TO ZERO AND, CONSEQUENTLY, THERE IS NO ADDED RANDOM DELAY.

THE FOLLOWING PRINTOUT, SWITCH TIMES WHICH ARE USED FOR EACH ENERGIZATION ARE TABULATED, FOLLOWED BY PEAK
OUT-VARIABLE VALUES WHICH OCCUR FOR THE ASSOCIATED SIMULATION.   FORMAT FOR PEAK VALUES IS IDENTICAL TO THE
NTOUT FOR MAXIMUM VARIABLE VALUES OF A CONVENTIONAL (I.E., NON-STATISTICAL) STUDY, TO WHICH PRINTOUT OF THE
EREACE ANGLE IN DEGREES HAS BEEN ADDED AT THE EXTREME LEFT.
 FIRST    0  RESULTS ARE NODE VOLTAGES (TO LOCAL GROUND).
 NEXT     2  RESULTS ARE BRANCH VOLTAGES.

                         GENA          GENB
F. ANGLE                 A1            B1

                          SWITCH CLOSING TIMES FOR ENERGIZATION NUMBER   1
                            1      .205114E-02   2     .457121E-02   3     .670617E-02   4     .800000E-02   5     .100000E-01
                            6      .120000E-01
.0000         .131473E+03   .160875E+03

                          SWITCH CLOSING TIMES FOR ENERGIZATION NUMBER   2
                            1      .190020E-02   2     .332777E-02   3     .481278E-02   4     .800000E-02   5     .100000E-01
                            6      .120000E-01
```

Of 6 data case switches, those numbered 1, 2, & 3 are "STATISTICS" switches



Only 2 output quantities, voltage differences, were requested

Peak overvoltages of 1st energization

1st two random times from model with $\bar{T} = .006$, $\sigma = .001$

⋮ Etc. for 6 energizations

An illustrative sample of "Output c" for a small statistical overvoltage study of NENERG = 6 energizations appears as follows. Of the several tabulations, only that for node voltage "A5 " is shown:

```
-----------------------------------------------------------------------------------------------------------------------

STATISTICAL DISTRIBUTION OF PEAK VOLTAGE AT NODE  'A5      ' .      BASE VOLTAGE FOR PER-UNIT PRINTOUT =    .30300E+03
   33
INTERVAL            VOLTAGE            VOLTAGE IN         FREQUENCY       CUMULATIVE           PER CENT
 NUMBER          IN PER UNIT        PHYSICAL UNITS       (DENSITY)        FREQUENCY         .GE. VOLTAGE
    24              1.15000           .348450E+03              0                0              100.000
    25              1.20000           .363600E+03              1                1               83.333
    26              1.25000           .378750E+03              0                1               83.333
    27              1.30000           .393900E+03              0                1               83.333
    28              1.35000           .409050E+03              1                2               66.667
    29              1.40000           .424200E+03              1                3               50.000
    30              1.45000           .439350E+03              0                3               50.000
    31              1.50000           .454500E+03              0                3               50.000
    32              1.55000           .469650E+03              0                3               50.000
    33              1.60000           .484800E+03              0                3               50.000
    34              1.65000           .499950E+03              0                3               50.000
    35              1.70000           .515100E+03              2                5               16.667
    36              1.75000           .530250E+03              1                6                 .000
DISTRIBUTION PARAMETERS FOR THE ABOVE DATA.    GROUPED DATA     UNGROUPED DATA
                                  MEAN =       1.5166667          1.5374122
                              VARIANCE =        .0526667           .0525309
                          STD DEVIATION =        .2294922           .2291963
-----------------------------------------------------------------------------------------------------------------------
```

sample variance, $\bar{\sigma}_V^2 = \sum_{j=1}^{N} (V_j - \bar{V})^2/(N-1)$

$\bar{\sigma}_V = \sqrt{\bar{\sigma}_V^2}$

sample mean, $(\sum_{j=1}^{N} V_j)/N = \bar{V}$ where V_j is the peak voltage at node "A5", during solution of energization "j".

Note: The "ungrouped" statistics are calculated using exact solution maxima, while the "grouped" statistics are calculated using discretized, compartmentalized values (rounded to multiples of .05).

1.9 USER SPECIFICATION OF SOURCE FUNCTIONS $f(t)$ FOR TYPE 1-10 SOURCES

1.9a. Introduction

Section 1.6 indicated that source types 1 through 10 are reserved for functions which the user wants to define himself, functions which are not provided for by the sources of type-code 11 onward. The user can resort to any of the following three procedures for defining his unorthodox sources:

Procedure 1 : Define the source functions $f(t)$ empirically at every time step that it is to be nonzero, and punch such points on data cards which then become part of the EMTP data case. Details are given in Section 1.9b below.

Procedure 2 : Define one or more source functions $f(t)$ to equal a TACS variable value. See Section 1.0g2 .

Procedure 3 : Define one or more source functions $f(t)$ analytically, and develop the FORTRAN logic which will return the desired value for any given input time. This becomes the user's own special subroutine "ANALYT" , for which he is responsable. The user must replace the original dummy EMTP module of this same name by his own module, before executing the data case in question. A special request card reading "ANALYTIC SOURCES" is also required (see Section 1.0g1).

Details of these procedures shall be elaborated upon below. Yet, if the user is employing the "ANALYTIC SOURCES" feature for the first time, he should definitely talk with Program Maintenance before proceeding too far. Reference to Section 0.5 might also be helpful, since details of how the user will perform his module replacement are definitely a function of the computer system being used.

1.9b Definition of $f(t)$ empirically, at every time step (Procedure 1)

If the user is willing to numerically punch his desired source values $f(t)$ on cards for every time step, then, the following is the procedure that he is to follow. See Section 1. for correct position of these data cards within the data case in question.

RULES:

1) The values of the curves $f(t)$ at $t = \Delta t, 2\Delta t, 3\Delta t, \ldots$ must be supplied in the correct time order with one card for each time step. Note that the first card is for $t = \Delta t$ (not $t = 0$, which belongs to the initial conditions).

Format for empirically specifying source types 1-10

type 1	type 2	type 3	type 4	type 5	type 6	type 7	Etc →
E8.0	E8.0	E8.0	E8.0	E8.0	E8.0	E8.0	

2) If all 10 source functions become zero prior to $t = t_{max}$, then punch "9999" in col 5-8 on that card where they are all zero for the first time. Then the functions in that and all subsequent time steps will be regarded as zero. No more cards must follow the 9999 - card.

3) If at least one of the source functions in the 10 fields is non-zero all way to t_{max}, then a stack of exactly n cards with no blank card for termination must be supplied, where:

$$n = \frac{t_{max}}{\Delta t}, \text{ rounded to nearest integer:}$$

Examples: $t_{max} = 0.0105$, $\Delta t = 0.005$		$n = 2$
$t_{max} = 0.0130$, $\Delta t = 0.005$		$n = 3$
$t_{max} = 0.0098$, $\Delta t = 0.005$		$n = 2$

1.9c Definition of One or More Source Functions f(t) Analytically (Procedure 3)

Either as an alternative to, or as a supplement to, the representation of Section 1.9b , the user is permitted to define one or more of the ten possible source functions f(t) in FORTRAN, within subroutine "ANALYT" . Relevant rules and restrictions related thereto include the following:

Rule 4: Begin the data case with an "ANALYTIC SOURCES USAGE" data card (see Section 1.0g1). To appear before the miscellaneous data cards, this record tells the EMTP to employ subroutine "ANALYT" of Rule 5.

Rule 5 : In FORTRAN, the user must write the computer code of subroutine "ANALYT" which defines the one or more needed functions for any time value t . Comment cards within the dummy UTPF module which is to be replaced by the user document the interface requirements:

```
M12. 530      SUBROUTINE  ANALYT
M13.1317C)    THIS MODULE IS CALLED BY SUBROUTINE  'SUBTS3'  OF OVERLAY 16
M13.1320C)    (OVERLAY 16 IF ECS OVERLAYING IS USED ON CDC) IF AND ONLY IF THE
M13.1321C)    DATA CASE BEING SOLVED USES ONE OR MORE SOURCES OF TYPE 1 THROUGH
M13.1322C)    10, AND ALSO HAS A SPECIAL   'ANALYTIC SOURCES'  REQUEST CARD.
M13.1323C)    WHICH PRECEDES THE MISCELLANEOUS DATA CARDS.   IF THIS BE THE
M13.1324C)    CASE, THE USER MUST REPLACE THIS DUMMY MODULE WITH ONE WHICH PUTS
M13.1325C)    ONE OR MORE SOURCE VALUES IN VECTOR  'VOLT'  AT EACH TIME STEP.
M12. 538C     RELEVANT VARIABLES TO USE IN THIS DEFINITION PROCESS ARE .....
M12. 539C        T     ----- TIME IN SECONDS FOR WHICH SOURCE VALUES MUST BE
M12. 540C                    ASSIGNED.
M12. 541C        ISTEP ----- THE TIME-STEP NUMBER.
M12. 542C        DELTAT ---- THE TIME-STEP SIZE.      A CONSTRAINT AMONG THESE
M12. 543C                    THREE VARIABLES IS       T = ISTEP*DELTAT  .
M12. 544C        VOLT  ----- VECTOR OF SOURCE VALUES.    FOR THE SOURCE HAVING
M12. 545C                    TYPE-CODE  'K' ,   VOLT(K)  MUST BE ASSIGNED
M12. 546C                    TO EQUAL THE DESIRED SOURCE VALUE AT TIME  'T' .
M12. 547C     SINCE THE PRESENT DUMMY MODULE HAD BETTER NEVER BE CALLED, THE
M12. 548C     FOLLOWING STATEMENTS WILL KILL THE RUN WITH AN APPROPRIATE ERROR
M14.2604C     MESSAGE.   THE ONE EXCEPTION IS FOR UTPF TEST CASE NUMBER 11,
M14.2605C     WHICH HAS   NTOT = 3  ,   IBR = 3  ,   AND   DELTAT = 0.1  .
M12. 551      INSERT DECK BLKCOM
M12. 552      IF ( NTOT  .NE.  3 )   GO TO 9000
M14.2606      IF ( IBR   .NE.  3 )   GO TO 9000
M14.2607      D1 = (DELTAT - 1.0/10. ) * 100.
M12. 517      IF ( ABSZ(D1)  .GT.  TENM6 )   GO TO 9000
M12. 556      IF ( VOLT(2)  .NE.  0.0 )   GO TO 9010
M12. 557      D1 = T - 0.25
M12. 558      VOLT(2)  =  100. - 100.*D1
M12. 559      IF ( T  .GT.  0.75 )  VOLT(2) = 0.0
M12. 560 9010 RETURN
M12. 561 9000 KILL = 104
M12. 562      LSTAT(19) = 9000
M12. 563      RETURN
M12. 564      END
```

For nearly all computer systems of interest, the user can save quantities from one time step to the next in storage which is local to "ANALYT" , even though the integrity of such storage is not guaranteed by new ANSI 77 FORTRAN rules, I am told. If there is any question on this point, consult with a FORTRAN expert for the computer system of interest.

Rule 6 : Any function definition f(t) within subroutine "ANALYT" are applied by the EMTP after the empirical definitions of Section 1.9b, thereby overriding such empirical definitions. It is this sequencing which shows how and why it is possible to use a combination of the two definition procedures:

a) Always, when using the "ANALYTIC SOURCES USAGE" option, data cards of Section 1.9b must be supplied. If no functions f(t) are to be so defined empirically, then it is just the single 9999-card which is required.

b) Upon the call to subroutine "ANALYT" , vector VOLT(10) will contain values as they were read from the ten source fields of the Section 1.9b empirical source-definition data cards. Or, if the terminating 9999-card has already been read, VOLT(10) will be identical zero. These input values for vector VOLT(10) can of course be used in the logic of subroutine "ANALYT" , if desired.

1.9d Sample Illustrative Usage of Analytic Type 1-10 Source Definition

Suppose that the following two sources are desired, as part of some particular EMTP data case:

Source 1 : A voltage source v(t) which is defined empirically (point by point), except that when such values are found to be non-positive, the following alternative assignment applies:

$$v(t) = \max \left\{ \begin{matrix} -3.6 \\ -5.4 \cos^2(120\pi t + 60^\circ) \end{matrix} \right\}$$

Source 2 : A sinusoidal voltage source, where the phase angl varies periodically, cyclically. Such might not be an unreasonable first approximation for a generator which is "swinging" in the transient stability sense, due to a system disturbance. Suppose we want:

$$v(t) = 303000 \cdot \cos(120\pi t + \delta(t))$$
$$\delta(t) = 30^\circ + 10^\circ \cdot \cos(5t + 90^\circ)$$

The user can supply any number (from zero on up) of data cards defining source number 1 empirically, terminated by a 9999-card if such definitions do not extend through the final time step. The following subroutine "ANALYT" will then complete the job of defining the two desired sources:

```
      SUBROUTINE  ANALYT
```

Insert the current EMTP /BLANK/ here. On CDC, this just takes the single record *CALL,BLKCOM ; on Univac, the single record INCLUDE BLKCOM suffices. Other systems may require the full set of 50 or so records. Don't forget appropriate variable type specifications, if any (such as IMPLICIT REAL*8 for IBM, generally).

39c

```
      IF ( VOLT(1)  .GT.  0.0 )  GO TO 1492
      D1 = TWOPI * ( 60. * T + 1./6. )
      D1 = -5.4 * COS(D1) **2
      IF ( -3.6  .GT.  D1 )  D1 = -3.6
      VOLT(1) = D1
 1492 D1 = COS( 5.0*T + TWOPI/4.0 )
      D1 = 30.  +  10.*D1
      D1 = TWOPI * ( 60.*T + D1 / 360. )
      VOLT(2)  =  303000. * COS ( D1 )
      RETURN
      END
```

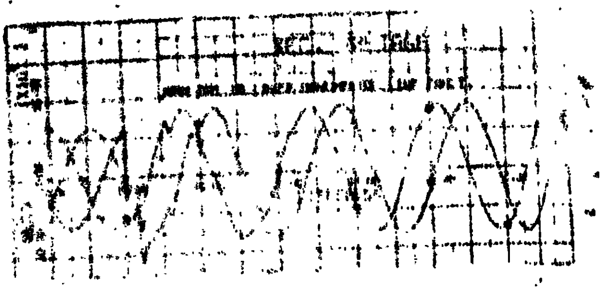
1.9e Definition of Type 1-10 EMTP Sources using TACS (Procedure 2)

Procedure 2 (the use of TACS) for the definition of Type 1-10 EMTP sources is straight forward. The user must of course define whatever TACS dynamics he desires, as explained in the TACS data instructions of Section 8. He also must indicate which source is to be controlled by which TACS variable, using a "TACS EMTP SOURCES" card of Section 1.0g2. That's all there is to it.

Note about hierarchy of procedures

The three procedures which have been described above are applied to Type 1-10 sources in the order that they are numbered. That is, Procedure 1 first, etc. :

1) First a data card is read, if it exists (if the bounding flag "9999" has not yet been encountered); all ten source values are defined therefrom.
2) Next, any "TACS EMTP SOURCES" definitions will over-ride the Procedure 1 assignments for those sources.
3) Finally, module "ANALYT" (if user-supplied and active) will modify the result of the preceding step in a way which is known only to the user. Note that further analytical processing of TACS dynamics is in this way possible, before the values actually are applied to the Type 1-10 EMTP sources.



1.10 CARDS FOR BATCH-MODE PLOTTING

Cards of this type are required for the input of additional data associated with the plotting of EMTP solution variables as functions of time. This is batch-mode plotting, with results available either on the computer-driven X-Y plotter (Calcomp plotter), or on the line printer (printer plotting). Interactive CRT plotting is done separately from the EMTP data-case setup, so is not described here (see Section 5.0).

A. General Rules and Procedures Concerning Batch-Mode Plotting

Rule 1 : Variables are available for plotting only if they have been previously requested for output as per Section 1.8 .

Rule 2 : Any number of plots can be made from any one solved data case. Up to four curves per plot are permitted. Only curves of the same type (among the five different classes : node voltage, branch voltage, branch current, branch power, branch energy) can generally be plotted on the same graph.

Rule 3 : Three graphing modes are available for batch-mode plotting, as the user is assembling his card deck of plot requests:

a) A graph just on the Calcomp pen-and-ink plotter. This will be referred to hereafter as the "CALCOMP PLOT" mode of operation, after the special request card bearing this text. See Section 1.10-B-9 .

b) A graph just on the line printer. This will be referred to hereafter as the "PRINTER PLOT" mode of operation, after the special request card bearing this text.

c) The same graph on both the Calcomp plotter and the line printer. This will be referred to hereafter as the "CALCOMP PRINTER" mode of operation, after the special request card bearing this text.

The user is free to switch back and forth among these three modes, during the course of his plot requests (see Section 1.10-B-9). "CALCOMP PLOT" is of course the most accurate and the nicest, while "PRINTER PLOT" is generally the least demanding of computer job time (not to mention the much faster actual plot time).

Rule 4 : Branch or switch current, power, or energy plots for two or more elements which are connected in parallel are not possible at the present time. As plot branches are identified only by terminal node-pair names, the program will always pick the first of the two or more qualifying candidates which it finds in the output vector. Refer to Section 1.8-A for a remedy, should this restriction bother the user.

Rule 5 : There is no limit on the number of data points which go into the production of each plot. If the array into which the data is read should become filled, and more data is needed, logical unit number 9 (the disk) is used for overflow storage.

Rule 6 : There are 13 different types of cards which may be used in requesting batch-mode graphs from the EMTP; the plot cards as a group or class of data will generally consist of a controlled mixture of these types;

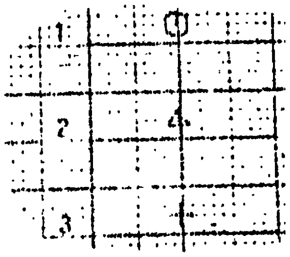
1. Card bearing 78-character case title text.
2. Cards bearing graph subheading text.
3. Plot specification card.
4. Card for specification of 3 or 4 branch node-pair names (special request word "BRANCH"),
5. Card for extended precision of floating-point fields (special request by card time-scale),
6. Card for Calcomp graph-size adjustment (special request word "HEIGHT"),
7. Card for Calcomp graph-separation adjustment (special request word "MARGIN"),
8. Card for redefintion of smoothing tolerance ϵ (special request word "SMOOTH").
9. Card for changing the graphing-mode selection (special request words "PRINTER PLOT" , "CALCOMP PLOT" , and "CALCOMP PRINTER"),
10. Card for changing the plotter print-head status (special request words "PRINT HEAD OFF" and "PRINT HEAD ON"),
11. Card for changing the pens which are used to draw each curve, plus control of the drawing of a grid (special request word "PEN CHOICE"),
12. Card for redefinition of line limit for sparse printer plots (special request word "PLOT LINE LIMIT").
13. Card for requesting that two or more plot cards be plotted on the same graph, with possible suppression of vertical-axis labeling (special request word "SUPERIMPOSE"),
14. Card for the photographic magnification or reduction of a plot image, with special application to metric plotting (special request word "SCALE").
15. Card to plotting one EMTP variable against another (special request word "X-Y PLOT").
16. Card for switching from plotting to Fourier series (special request word "FOURIER ON").
17. Card for switching from Fourier series to plotting (special request wword "FOURIER OFF").
18. Card to mark the termination of all preceding plot cards.

Of the above card types, only the plot specification card of number 3 is actually required to produce a plot: there will be one graph for each such card. A detailed description of the format and [illegible] under function of all of these cards will be found in Section 1-10-B, under the numbers which are used above.

Rule 7 : The one to four curves which can appear on the same graph are identified by the following symbols and node names:

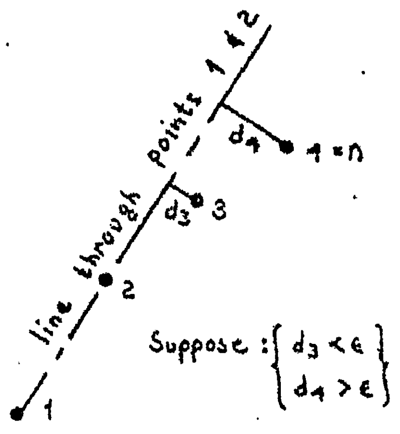
Curve number	Printer Plot	Calcomp Plot	Name for node voltage is read from columns:	[illegible] names for branch or switch output ([illegible] information) is read from columns:
1	A	Ⓘ	25 - 30	25 - 36 — 1st node pair
2	B	△	31 - 36	37 - 48 — 2nd node pair
3	C	+	37 - 42	49 - 60 } Three or more branch quantities require use of special "BRANCH" request.
4	D	X	43 - 48	61 - 72
Intersection of 2 or more curves	*			

In the upper right hand corner of every plot, there will be a legend which shows the symbol, the curve number, and a sample line drawn by the pen --- for each curve. An illustration for a case with three curves follows:



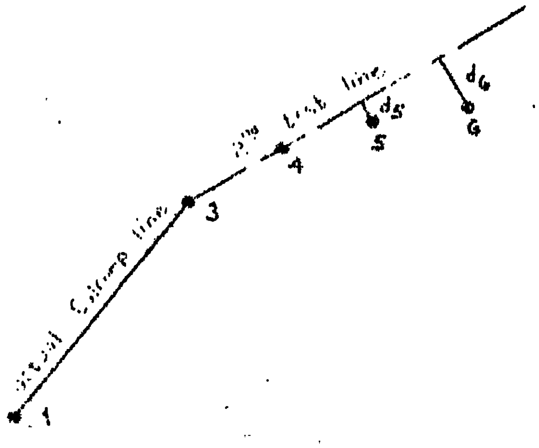
The output frequency of the curve-indication symbols on the Calcomp plots corresponds to every one inch for the unsmoothed (raw) data; larger separations which will generally be observed allow for estimation by the user of what fraction of the data points has been discarded during "smoothing" (see Rule 8 below).

Rule 8 : If a Calcomp plot is to be made, the program first discards those data points which will not visually affect the plot, according to the following algorithm. This is the so-called "smoothing" algorithm:



line through points 1 & 2
d_4
4 = n
d_3
3
2
1
Suppose : $\left\{ \begin{matrix} d_3 < \epsilon \\ d_4 > \epsilon \end{matrix} \right\}$

Initial test line



2nd test line after discarding pt. 2.

The first point of raw plot data is always retained, and an imaginary line is drawn from it through the second point of plot data. Starting with the third point, then, the distance d of each succeeding point from the line is calculated, and compared to a smoothing tolerance (see Rule 6, Point 8) ϵ :

a) As long as $d \leq \epsilon$, the distance calculation is simply repeated for the following point.

b) Eventually, for some n it is found that the n-th point is further removed than ϵ from the line ($d > \epsilon$). In this case, the (n-1)-st point is saved, and all points between the (n-1)-st point and the last previously-saved point are discarded. This is based on the principle that throwing away such points will not significantly affect the resulting graph visually, since they lie on, or almost on, the line about which the distances were calculated.

Such distance-testing is then continued recursively, following the sample just outlined. It is begun by drawing a new line from the (n-1)-st point through the n-th point, and then checking distances from this new line for points numbered n+1 onward.

The one exception to the distance comparison based on ϵ as just described is that pertaining to relative minima or relative maxima; such a point of relative extremum is always saved, regardless of its distance from the line. In effect, $\epsilon = 0$ is used for the calculation at extrema.

The value of smoothing tolerance ϵ is under user control, by means of a special "SMOOTH" request card. Details are covered in Section 1.10-B-8 .

Line printer plotting is executed before smoothing occurs. Thus if only this mode of batch-mode plotting is being used (the last request of Rule 6, Point 9 was "PRINTER PLOT"), the entire smoothing process is bypassed, and not executed. But if both modes of plotting are currently activated (the last request of Rule 6, Point 9 was "CALCOMP PRINTER"), the raw data points are first plotted on the line printer, then they are smoothed and plotted on the Calcomp plotter.

Rule 9 : The user has control over whether all plots are to be positioned end-to-end horizontally (down the length of the graph paper), or are also to be lined up vertically as well (as permitted by the paper width). For example, consider the following contrasting situations:

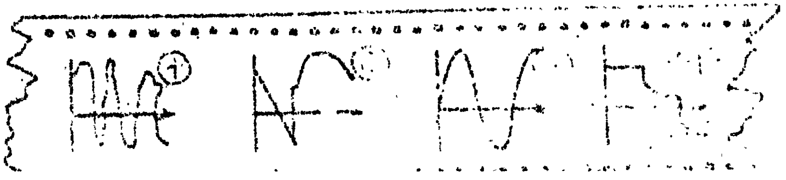


Fig. 1. All plots positioned horizontally.

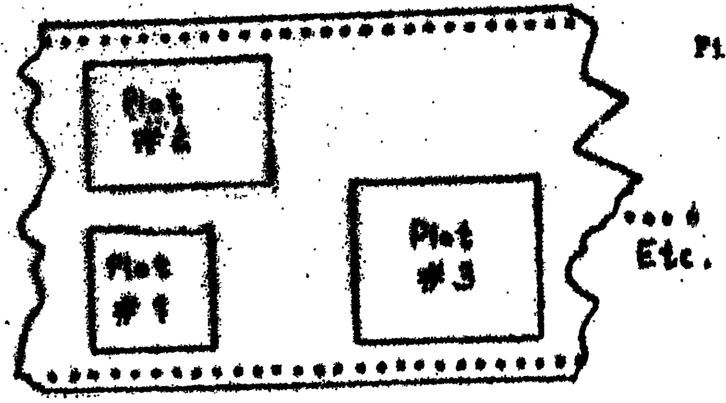


Fig. 2. Plots positioned vertically as well as horizontally.

The general rule as to EMTP batch-mode plotting is as follows: plots are positioned vertically (one on top of the other) until the paper width would be exceeded; then the process begins at the bottom again, to the right of the just-completed plots. The first plot of a new data case automatically begins at the bottom of the paper, too.

User control of this graph-positioning process (vertical stacking) is by means of the following variables:

"SZPLT" ——— Paper width (height as used here), as described in Section 1.0c .

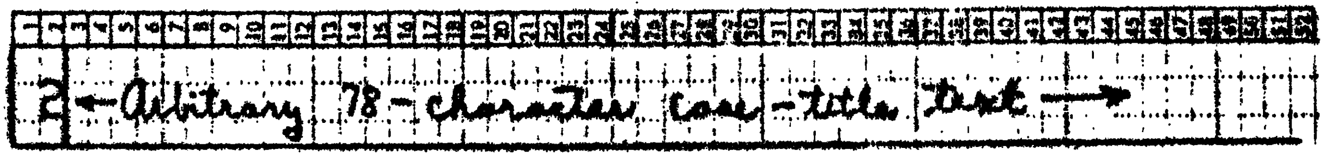
"BEGIN" "SPAN" ——— Height of each individual plot, as defined by a "HEIGHT" card. See the description of Section 1.10-B-6 .

Recall that default values exist for these, assuming that they are not re-defined by the user. In June of 1977, CDC translations were using 10. , 1.0 , and 8.0 inches for these, respectively. Using these just-stated values would give the horizontal positioning of Fig. 1 above, regardless of the actual width (height) of the plot paper. On the other hand, changing "SZPLT" to 24.0 inches would result in the positioning of two plots vertically as shown in Fig. 2 above ——— again regardless of the actual width of the plot paper. Of course if the actual paper width is less than "SZPLT" , the pen will attempt to move off of the paper (not a very satisfactory situation). It is the user's responsibility to see that the paper is at least as wide as the "SZPLT" value which is being used, then.

B. Input Data Card Format, for Batch-Mode Plotting

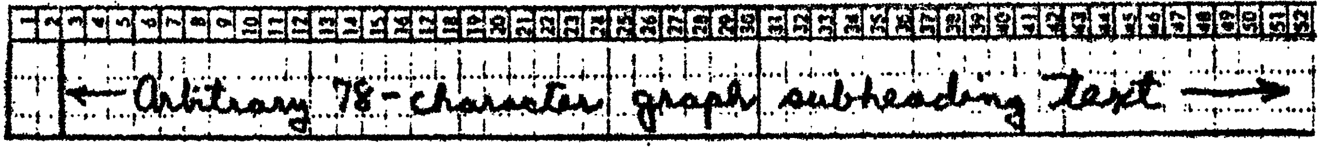
Point 1 : Card bearing 78-character case-title text

This card has a "2" punched in column number 2 , followed by up to 78 arbitrary characters of case-title text. This text will then appear at the top of all plots which are requested after this definition ---- until redefined t some later stage of the plot-data input. Blank text is automatically provided on all plots which precede the user's first definition. Height of lettering on the Calcomp for this text is 0.12 inches. The format for data input is:



Point 2 : Cards bearing graph subheading text,

Zero to four such data cards for defining graph subheading are permitted, the text of which will appear as a subheading on only the immediately following graph. Each line is 78 characters in length, with the lettering being 0.1 inches high on Calcomp plots. Each subheading data card is to have columns 1-2 blank, with the aribitrary text then punched in columns 3-80 , as per the following format:



Point 3 : Plot specification card

This is the only plot card type actually required in order to produce a graph; there will be one graph produced on the Calcomp and/or line printer for each such plot card. The card format is as follows (see following page for diagram):

Cols. 1-2 -------------- Punch a "1" in column 2.

Col. 3 -------------- Punch an integer which depends upon the type of variables being plotted:

1) For node-voltage plots, punch a "4" if all curves regardless of number are desired on the same plot.

If the requested curves are to be divided among two or more plots, punch the number of curves which are to appear on the same graph, maximum.

BONNEVILLE POWER ADMINISTRATION

FORTRAN CODING FORM

Requested by ____ Ext N. ____ Job cod ____ Project ____ Sheet ____ of ____

Statement No.				120	STATEMENT									Identification
1-2	3	4	5-6	7-11	12-15	16-20	21-24	25-30	31-36	37-42	43-48	49-64	65-72	73-80
"1" in column 2	[illegible] type code	UNITS ON HORIZ. SCALE	HORIZONTAL SCALE (units per inch)	TIME WHERE PLOT STARTS (in scale of col. 4)	TIME WHERE PLOT ENDS (in scale of col. 4)	VALUE AT BOTTOM OF VERTICAL SCALE	VALUE AT TOP OF VERTICAL SCALE	UP TO 4 NODE NAMES FOR NODE VOLTAGE PLOTS or UP TO 2 PAIRS OF NODE NAMES FOR BRANCH OR SWITCH PLOTS				GRAPH HEADING LABEL	VERTICAL AXIS HEADING LABEL	
								1st Element		2nd Element				
								1st voltage	2nd voltage	3rd voltage	4th voltage			
I2	I1	I1	E3.0	E4.0	E4.0	E5.0	E4.0	A6	A6	A6	A6	2A6, A4	2A6, A4	

"1" DEGREES
"2" CYCLES — based on the synchronous power frequency "STATFR"
"3" SECONDS
"4" MILLISECONDS
"5" MICROSECONDS

EXAMPLE:

```
1442.08.0030.0-0.500.50 THREE  FOUR  FIVE        TWO CYCLE TEST  VOLTAGE PER UNIT
1942.08.0030.0          A1     A2    B1    B2                    CURRENT
```

4 voltages are plotted on the first plot and 2 currents on the second plot. The scale on the second plot is chosen by the computer.

10d

(43)

ii) For voltage differences or powers of branches or switches, punch an "8" in column 3.

iii) For currents or energies of branches or switches, punch a "9" in column 3.

Remember that dynamic synchronous machine variables are all plotted as though they were branch currents, so they use a "9" punch too.

Col. 4 ———— A code number indicating which units are desired for the time axis. Floating-point time specifications to follow are then assumed to be in these units:

"1" ——— for degrees
"2" ——— for cycles

} Based on the synchronous power frequency "STATFR" (see Section 1.0c for redefinition).

"3" ——— for seconds
"4" ——— for milliseconds
"5" ——— for microseconds
"6" ——— for frequency in Hertz
"7" ——— for the base-ten logarithm of "6"

Note: "6" and "7" are applicable to Bode plots only ——— the plotting of phasor solutions in the frequency domain only. See Section 1.0g3 .

Cols. 5-7 ———— The desired horizontal scale "HPI" in time units (whatever they may be, from the col. 4 request) per inch.

For example, if the user punches "3.0" in columns 5-7, and "4" in column 4, then he will get a time axis with scaling 3.0 msec/inch .

A blank or zero field has special significance, as a request for extended floating-point precision for plot-card input fields (see Section 1.10-B-1).

Cols. 8-11 ———— The beginning time "HMIN" where the time axis will start, in units of whatever the user has selected by his column-4 punch.

Cols. 12-15 ———— The final time "HMAX" where the time axis will end, in units of whatever the user has selected by his column-4 punch.

The curves will be plotted from the left graph limit "HMIN" to the right graph limit "HMAX" only; these limits themselves will generally lie somewhere in the study time-range of zero to "TMAX" (floating-point miscellaneous data parameter; see Section 1.0h) seconds.

Cols. 16-20 ------------ Value at bottom of vertical axis, "VMIN". This is the minimum ordinate on the scale. Leave blank if automatic scaling is desired.

Cols. 21-24 ------------ Value at top of vertical axis, "VMAX". This is the maximum ordinate on the scale. Leave blank if automatic scaling is desired.

Further comments about "VMIN" and "VMAX"

Parameters "VMIN" and "VMAX" only have meaning for plotting on the Calcomp plotter, since line printer plots are always automatically scaled so as to utilize the full 132 characters of carriage width.

In cases where the minimum and maximum values of the one or more curves for a given Calcomp graph are not known in advance, it is usually convenient to let the EMTP decide upon the appropriate vertical scaling. This is requested by leaving fields "VMIN" and "VMAX" blank.

In order for the "tic" marks on the vertical axis of a Calcomp plot to correspond to nice round numbers, the variable span of that axis (VMAX - VMIN) should be divisible evenly by the axis length in inches. The axis length is under user control (see Section 1.10-B-6), although it is normally left at its installation-dependent default value (typically 8.0 inches; see Section 0.5).

Cols. 25-30, 31-36, 37-42, 43-48 ------------ Network node names are read from the four A6 fields which are contained in the columns 25-48. These identify the curves to be plotted, as follows:

i) For node-voltage plots, the name or names of the nodes in question are to be punched. Any of the four name-fields can be left blank, if not needed.

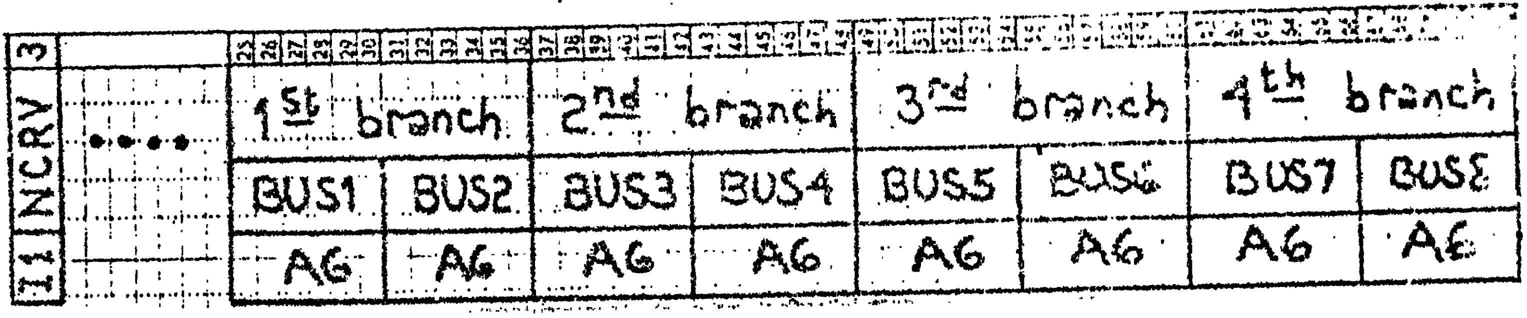
ii) For branch or switch variables (element voltage difference, current, power, or energy), punch either one or two node-pair names which identify the branches in question. Columns 25-36 are for one branch, and columns 37-48 for another.

If more than two branch or switch variables are desired on the same graph, the user should punch the special request word "BRANCH" in cols. 25-30; then the EMTP will read the node-pair names for up to four elements from a following card, as detailed in Section 1.10-B-4.

Cols. 49-64 ————————	16 arbitrary alphanumeric characters, to be used as the main graph heading label. On the Calcomp, this will be drawn with letters 0.20 inches in height.
Cols. 65-80 ————————	16 arbitrary alphanumeric characters, to be used to label the vertical axis of the graph.

Point 4 : Card for input of 3 or 4 branch-variable names

If the special request word "BRANCH" is punched in columns 25-30 of the plot specification card (Point 3), then the variable identification is not made using columns 25-48 as usual; instead, the EMTP will read such information from an additional card which immediately follows, where up to four node-pair variable identifications are to be provided:



NCRV ———	Leave blank if all curves are to be plotted on the same graph. A nonzero integer between 1 and 4 will be taken to mean the number of curves on the same graph. Such usage is rare.
BUS1, BUS2 ———	node-pair names for the first branch or switch which is to have its variable plotted on the graph.
BUS3, BUS4 BUS5, BUS6 BUS7, BUS8 } ———	Similar meanings for the 2nd, 3rd, and 4th branches or switches.

If any one of the four node-pair identifications contains two blank words (12 blank characters), the request is simply ignored.

Point 5 : Card for extended precision of floating-point fields

The five floating-point fields of the plot specification card, "HPI" , "HMIN" , "HMAX" , "VMIN" , and "VMAX" , all vary in width from three to five columns. Now, this is generally sufficient for typical production usage, in which nice round numbers such as 20.0 msec/inch for the horizontal axis scaling are typical. But the precise scaling of odd-ball tolerances such as 16-2/3 msec/inch is clearly impossible using such limited-precision fields for data input. The option described below removes this limitation.

For full 16-column-width precision in the specification of all five floating point plot-specification card parameters, the user need only leave columns 5-7 (field "HPI") of the plot-specification card blank. The program will then read an additional following card, from which it will extract the five variables in question, in the same order, using the following format:

HPI	HMIN	HMAX	VMIN	VMAX
E16.0	E16.0	E16.0	E16.0	E16.0

Exception : For a situation where the user desires to use both the "BRANCH" option of Point 4 and also the option just described, it is the present extended-precision card which is to be deferred:

1. Plot specification card with blank cols. 5-7, and "BRANCH" punched in columns 25-30.
2. Then the branch-variable name card of Point 4.
3. Then (finally) the extended-precision card immediately above.

Point 6 : Card for Calcomp graph-size adjustment

The bottom margin and vertical-axis height of a Calcomp plot are installation dependent, though typically set to default values of 1.0 inch and 8.0 inches, respectively. Either or both of these parameters can be changed by the user, as per a special request card having the following format:

ITYPE		BEGIN	SPAN		Special request word
1		E4.0	E4.0		HEIGHT

Cols. 1-2 ------- "ITYPE" , the card type-code is to be punched as unity.

Cols. 8-11 ------- "BEGIN" , the new lower margin in inches, read using E4.0 format.

Cols. 12-15 ------ "SPAN" , the new graph height (vertical axis span) in inches, read using E4.0 format.

Cols. 25-30 ------ The special 6-character request word "HEIGHT" .

All plots requested after input of this card will have this specified bottom margin and vertical-axis height, unless subsequently changed by another such card at a later stage of the plot-data input cards.

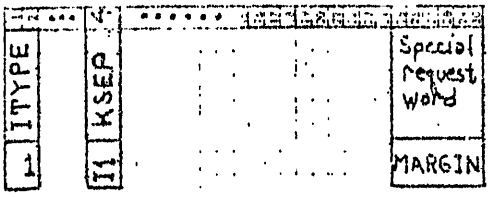
It might be mentioned that implicit to this discussion is the assumption that the operator will start the Calcomp plotter with the pen origin at the bottom of the graph paper; if not, the lower margin is simply relative to whatever point the operator initializes the origin at.

If the total distance represented by bottom margin "BEGIN" plus vertical axis height "SPAN" is greater than the installation-dependent plot-paper size "SZPLT", a message is printed on the line printer and the graph size-adjustment request in question is ignored by the EMTP. In this case, the program would continue to use the last legal values for "BEGIN" and "SPAN" --- either those originally set by default, or defined on a previous graph-size adjustment card. In this discussion, variable "SZPLT" is the total width of the plotting paper, the value for which is under user control as per Section 1.C .

Line printer plotting is completely unaffected by the presence or absence of such a graph-size adjustment card (since it only applies to the Calcomp).

Point 7 : Card for Calcomp graph-separation adjustment

The spacing between successive Calcomp plots is initially set by the program at the start of each new data case to an installation-dependent value of "KSEP" inches (an integer; usually equal to 2 inches). But such graph separation can be altered by the user at any stage of the plotting, by means of a card having the following format:



Cols. 1-2 ------- "ITYPE", the card type-code is to be punched as unity.

Col. 4 ----------- "KSEP", the inter-graph separation distance which is desired, as an integer number of inches between 2 and 9, inclusive.

Cols. 25-30 ------- The special 6-character request word "MARGIN".

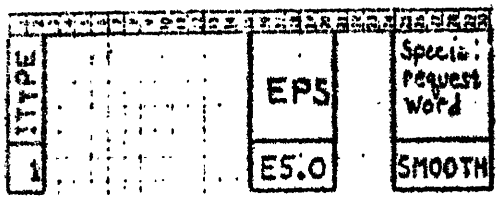
The inter-graph separation which is requested in this way will continue in effect for all Calcomp plots of a given data case until another such "MARGIN" request is encountered. But remember that each data case will automatically be initialized to the default value for "KSEP" at the very beginning; hence such "MARGIN" requests are only local to the data case of which they are a part.

Requested separations "KSEP" of less than 2 inches are rejected by the EMTP, with the preceding legal value (whatever it may have been) simply continuing in effect, in this case. A warning message of such a rejection is outputted to the line printer in such a case, for the user's benefit.

Line printer plotting is completely unaffected by the presence or absence of such a graph-separation adjustment card (since it only applies to the Calcomp).

Point 8 : Card for redefinition of smoothing toleranc ε

The numerical value for smoothing tolerance ε which was described in Section 1.10-A-8 is given a default value of 0.01 inches by the EMTP at the beginning of each new data case. However, its value is under user control, and can be changed from one plot to another by use of a special request card of the following format:



Cols. 1-2 ------- "ITYPE" , the card type-code is to be punched as unity.

Cols. 16-20 ------- "EPS" , the desired new smoothing tolerance ε in inches, read using E5.0 format.

Cols. 25-30 ------- The special 6-character request word "SMOOTH" .

A tolerance so defined will remain in effect for all Calcomp plots of the the data case in question which follow, until another such redefinition of ε is encountered.

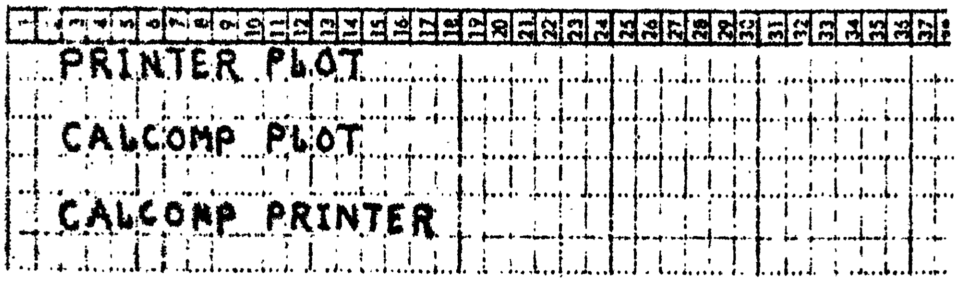
If the user defines "EPS" to be 0.1 inch or more, a warning message is printed out on the line printer. While relative extrema will be exact in such a case, the general plot shape begins to look significantly distorted, in general. The message just reminds the user why his plots look so jagged.

Should the tolerance field "EPS" be left blank or punched with a value of 0.0001 (inches) or less, the EMTP sets the tolerance ε identically to zero, and no smoothing at all occurs; the associated smoothing operations are completely bypassed, and all raw data points are plotted on the Calcomp.

Line printer plotting is completely unaffected by the presence or absence of such a smoothing-tolerance redefinition card (since it only applies to the Calcomp

Point 9 : Card for changing the graphing mode selection

At any stage of the plotting data-card input, the user can request that graphing be done either just on the Calcomp, or just on the line printer, or on both of these devices. This is as per Section 1.10-A-3 . A request for one of the three alternative graphing modes requires a card having one of the following formats:



Cols. 1-2 -------- Blank.

Cols. 3-17 -------- Special request-word text for the desired mode:

"PRINTER PLOT" makes the following plots come out just on the line printer.

"CALCOMP PLOT" makes the following plots come out just on the Calcomp plotter.

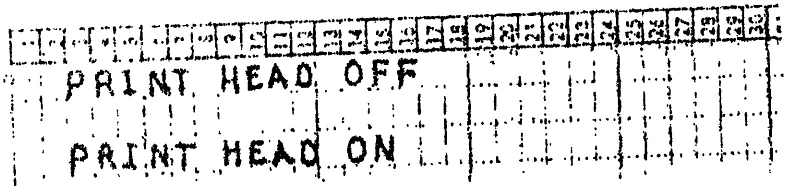
"CALCOMP PRINTER" makes the following plots come out on both the line printer and also on the Calcomp plotter.

The EMTP is initialized at the beginning of each new data case to just produce Calcomp plots. This or a later requested mode will remain in effect for the data case in question until changed by another such request card as above.

Point 10 : Card for changing the plotter print-head status

Some pen-and-ink plotters have the option of "typing" all character output using a print-head, rather than drawing such characters using the pen. Of course such lettering and numbering is not generally as pretty, and is of a uniform, small size (typically something like the capitol letters of a typewriter). But use of such a print-head reduces substantially the plotting burden on the computer, so is to be encouraged wherever available, and when aesthetics are not of prime importance.

The EMTP is set by default to begin the graphs of each new data case using the print-head, if it exists. A request for either mode of lettering is then acceptable at any point in the plot data cards for the data case, using the following format:



PRINT HEAD OFF

PRINT HEAD ON

Cols. 1-2 -------- Blank.

Cols. 3-16 -------- Special request-word text for the desired status of the print-head:

"PRINT HEAD OFF" makes the following Calcomp plots having lettering which is drawn by the pen.

"PRINT HEAD ON " makes the following Calcomp plots having lettering which is typed by the print-head, should the hardware capability exist.

The requested print-head status will remain in effect throughout the data case [illegible] until altered by another such request. Line printer plotting is [illegible] unaffected by such print-head status requests, of course.

Point 11 : Card for changing the pens and the grid status

Different curves of any plot may be drawn with different pens, if desired. mon usage is to either vary the boldness of black lines, or else to plot in color (with each curve being a different color). Such a choice of pens can be changed at will by the user —— from plot to plot, if desired.

The option of a pen-drawn grid for plots is also available. Common usage is for plotting on unruled (blank, pure-white) paper. Grid lines are drawn every inch, both horizontally and vertically, as extensions to the "tic" marks of the axes.

User control of the two preceding options is provided by a single card, which is to have the following format:

PEN CHOICE	I8	I8	I8	I8	I8
	KPGRID	$KPEN_1$	$KPEN_2$	$KPEN_3$	$KPEN_4$

Cols. 3-12 ———— Special request-word text "PEN CHOICE" is punched in this field.

Cols. 17-24 ———— "KPGRID" , the integer pen number (I8 format) which is to be used for drawing the grid. A zero or blank field will suppress the grid (i.e., none will be drawn).

Cols. 25-32
33-40
41-48
49-56 ———— KPEN(I) , the integer pen number (I8 format) which is to be used to draw curve number "I" of the plot. A zero or blank field is taken to mean no change in the pen number (from the preceding assignment) for the curve associated with that data field.

The requested pen choices and grid specification will remain in effect throughout the data case in question, until altered by another such request card.

Before the first appearance of such a card within any data case, the program automatically provides the following initialization:

$$KPGRID = 0 \qquad (KPEN(I) = 1 \ \text{for all} \ I)$$

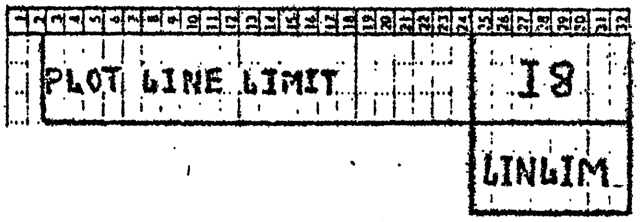
That is, there will be no grid, and all curves will be drawn with pen number 1 , unless an explicit request to the contrary follows.

Point 12 : Card for changing line limit on sparse printer plots

For curves where the number of raw plot data points exceeds the number of printed lines of a line printer plot, there is no problem with line limits on printer plots; printer plots can be of any length in this case.

But if the user requests more printed lines of time axis than there are raw plot-data points for that interval, then a special limit "LINLIM" comes into play. Such a "sparse" printer plot will be terminated when this line limit is exceeded ——— where "sparse" is defined to mean that there are fewer raw data points than printed lines. Such sparse plots are characterized visually by lines of plot output which have no curve symbols.

Sparse plot line-limit "LINLIM" has been given a default value of 100. This limit can be redefined by the user, however, using a special-request card of the following format:



Such a user-requested "LINLIM" will remain in effect throughout the data case in question, until altered by another such request card. A following data case will begin with the default value, however.

Point 13 : Card to superimpose plots and/or suppress vertical-axis labeling

It is not uncommon for the user to desire extensions to the basic plot capability of the Point 3 format. For example, he may want:

——— the plotting of more than 4 curves on the same graph, or

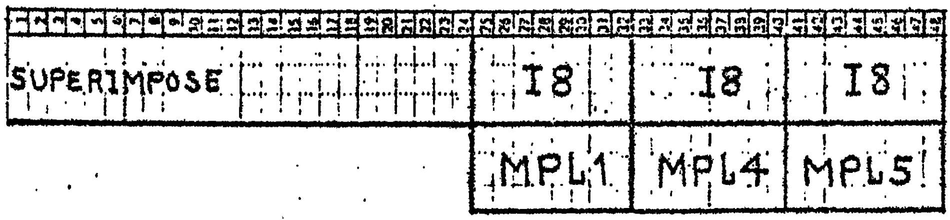
——— the plotting of different variable types (e.g., node voltages and branch currents) on the same graph, or

——— the addition of a vertical offset for one or more curves of a graph, or

——— suppression of the vertical-axis labeling (leaving just the vertical line with tic marks).

All of these operations are possible, by careful use of the powerful (but tricky) "SUPERIMPOSE" card.

User control of special features such as those just mentioned is by means of a special-request card having the following general format:



Columns 3-13	———	Special-request word "SUPERIMPOSE" is punched in columns 3-13.
MPL1 (24-32)	———	The integer number of plot specification cards (Point 3) which are to be superimposed. Any non-positive integer (e.g., zero or blank) will be defaulted to unity.
MPL4 (33-40)	———	A flag for possible suppression of the vertical-axis labeling. If no such labeling is desired, punch a "1" in column 40; otherwise, leave blank or zero.

MPL5 (41-48) ——— A flag for possible suppression of the vertical-axis labeling. If no such labeling is desired, punch a "1" in column 48 ; otherwise, leave the field blank, or punch zero.

This "SUPERIMPOSE" feature is very powerful, but also a little tricky. For this reason, it is desirable that the user understand a few basic operational principles, rather than just the plotted effect.

<u>Principle 1</u> : The superposition feature is based on suppression of the origin-changing operation which normally occurs upon the completion of a plot. If the change of origin is omitted, the following plot will be drawn on top (i.e., superimposed) of the preceding one. Thus the superimposed plots are really separate, independent EMTP plot; they are produced separately, just as would be the case if there were no "SUPERIMPOSE" card.

<u>Principle 2</u> : All non-curve inking for the second and later of a group of superimposed plots is automatically suppressed. Thus the grid (if requested), the axes, the date and time (etc.), and any title will only be drawn once ——— for the <u>first</u> of the superimposed plots. The scaling of the second and later superimposed plots is <u>not</u> documented on the plot, then, it will be noted.

With this underlying information now in hand, let us consider several cases of novel (but not uncommon) usage:

<u>Usage 1</u> : Suppose that the user wants to plot more than four EMTP variables on the same graph. He simply places these on as many different plot specification cards (Point 3) as he may require or desire, and then these are preceded by the appropriate "SUPERIMPOSE" card.

As an example of this usage, consider the required data cards for seven node voltages on the same graph:

```
SUPERIMPOSE                        3
 144 8. 0.0 80. -20. 20.NODE1 NODE5 NODE9
 144 8. 0.0 80. -20. 20.NODE3 NODE4
 144 8. 0.0 80. -20. 20.BLACK       BLUE
```

<u>Usage 2</u> : Suppose that the user would like to mix different plot-variable classes (e.g., node voltages and branch currents) on the same graph. Separate plot specification cards (Point 3) would be constructed for variables within any one class. These would then be preceded by the appropriate "SUPERIMPOSE" card.

As an example of this usage, consider the data cards which will plot two node voltages and one branch current on the same graph:

```
SUPERIMPOSE                        2
 144 8. 0.0 80. -20. 20.NODE3 NODE4
 194 8. 0.0 80. -4.0 4.0BUSK BUSM
```

Usage 3 : Suppose that the user wants to compare two or more curves which are similar. If such curves were plotted to the same scale on the same plot, it would be difficult to distinguish one from the other. One possible remedy is to offset one or more of the curves vertically. In the case of three curves, there would be 3 separate plot specification cards (Point 3); the vertical offset for each is produced by adding the appropriate constant to both "VMIN" and "VMAX" of columns 16-24 . As usual, such plot specification cards would be preceded by the appropriate "SUPERIMPOSE" card, in this case having a "3" punched in column 32 .

As an example of this usage, consider the case of three node voltages. The second is to be offset one inch above the first, and the third is to be offset one inch above the second. Also, vertical-axis labeling is to be suppressed, note:

```
SUPERIMPOSE                    3       1
 144 8. 0.0 80. -20. 20.NODE1
 144 8. 0.0 80. -25. 15.NODE2
 144 8. 0.0 80. -30. 10.NODE3
```

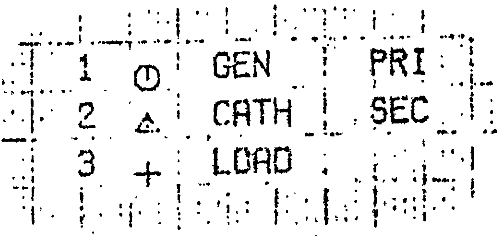
Usage 4 : Suppose that the user wants to suppress all axis labeling on a conventional plot (not uncommon in the case of publication). To do this, the usual plot card would be preceded by a "SUPERIMPOSE" card having a "1" punched in columns 40 and 48 . There will not actually be any superposition as such, of course. Rather, the user is merely exploiting the axis-labeling suppression which is available only via the "SUPERIMPOSE" feature.

As an example of this usage, consider the case of two node voltages, for which no vertical-axis labeling is desired:

```
SUPERIMPOSE                            1       1
 144 8. 0.0 80. -20. 20.NODE1       NODE9
```

In the case of "SUPERIMPOSE" usage, variable identification has been modified (compared with Rule 7) so as to account for a large number of variables. The curve number (e.g., "7"), the curve symbol (e.g., "+"), and the one or two 6-character identifying names are all drawn side by side. This begins in the upper right hand corner, and proceeds downward in order, spaced four per inch. A sample is shown at the right, below. Standard CalComp symbols have been used, the first few of which have the following correspondance:

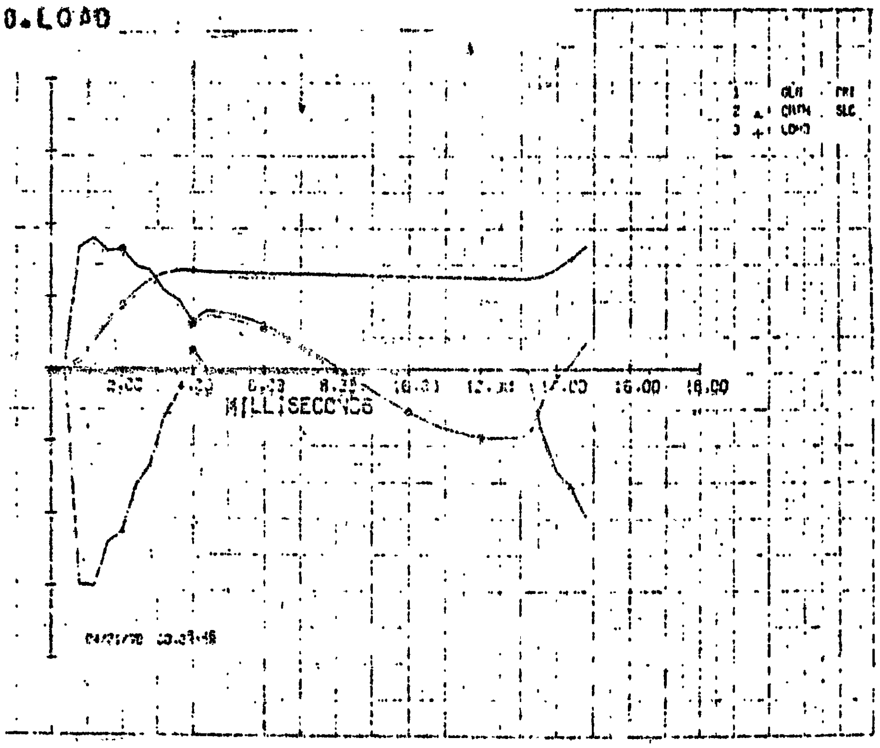
1	2	3	4	5	6	7	8	9
⦶	△	+	×	◇	↑	⧗	Z	Y



Vertical-axis scaling is unambiguous if th user does the scaling himself, manually (i.e., by punching fields "VMIN" and "VMAX" of columns 15-24 of the Point 3 plot-specification card). But if these vertical-axis fields are left blank, then the EMTP will perform its own scaling, and the user will be forced to figure this out after the fact for variables of the second and later plot-specification cards. Remember, only the vertical axis for the first such card is drawn, and even this can be suppressed if so desired by the user! As a general rule, it is recommend that the user do all of his own vertical-axis scaling, on those plots which involve the "SUPERIMPOSE" usage.

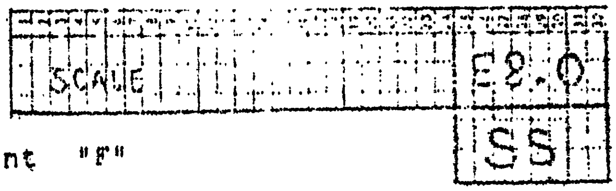
As for time-axis scaling, it is assumed that the user has enough sense to keep this the same for all superimposed plots, if this is what he really wants (and it normally is). There are exceptions, however, such as comparing different segments of the same curve. If the time-axis scaling is varied within a group of superimposed plots, the user is simply advised to be careful, and to remember what he did, since only the time axis of the first plot-specification card will be drawn on the graph.

```
PRINT HEAD OFF
SUPERIMPOSE                      2       1
194 2. 0.0 15. -12. 12.GEN     PRI    CATH    SEC
144 2. 0.0 15. -20. 20.LOAD
```



Point 14 : Card for photographic magnification or reduction

CalComp plotting software has a SUBROUTINE FACTOR(F) which allows for the photographic magnification or reeduction of a plot. It is by means of the key request word "SCALE" that this is made available to the EMTP plotter:



(3 - 7) ---- special request word "SCALE"

(25-32) ---- reciprocal of argument "F" of CalComp FACTOR .

with SS = 1.0 , there is no alteration of the plot size; for SS greater than unity, the plot contracts; and for SS less than unity, it expands.

The most common application is for metric plotting, in countries other than the USA and Canada, The idea is very simple: do the plotting with English units as described in the instructions, and then slightly contract the plot so that one inch will equal two centimeters. For this, one uses SS = 1.270025 . All labeling will then be a little smaller (by this factor), and axis "tic" marks and the optional ruled background grid will have separations of 2.0 centimeters. As an EMTP user, one simply mentally replaces all mention of "inches" in the instructions by "two centimeters" . For example, consider variable "HPI" of columns 5-7 of the plot-specification card. Instructions say that this is the number of time units (e.g., msec) per inch for the horizontal axis. But if one uses SS = 1.270025 , this is then to be read as the number of time units per two centimeters. That is, divide the number by two to get the number of time units per centimeter. It really is quite straightforward, then.

Point 15 : Card for plotting one EMTP variable vs. another

Historically, all EMTP plotting was done with one EMTP variable on the vertical axis (ordinate), and with time on the horizontal axis abscissa). But. subject to some restrictions, and with use of the special request "X-Y PLOT" , the user is able to plot one EMTP variable as a function of the other, as first described in Ref. 8, Vol. VIII, 27 January 1979, pages PROV-9 onward. The following description is reproduced from that presentation.

Rules for the new "X-Y PLOT" feature are really quite simple, summarized by the following:

Rule 1 : Some of the old EMTP batch-mode plotting cards are honored, and some are not. We have:

a) The cards which are honored include the case title and graph subheading cards (see Rule 5 , Points 1 and 2 on page 40a of the User's Manual). The same goes for the "PEN CHOICE" card of Point 11 , and the print head cards of Point 10 . Finally, the "BRANCH" request of Point 4 is accepted if more space is required for specification of the variables.

b) Other special requests or features in the list are not honored, so should not be used by the user.

43f

Rule 2 : Three special, new cards signal the request for "X-Y PLOT" usage:

Card 1 :

X-Y PLOT	4A6
request word	Horizontal axis label

(3-10) —— Special request word "X-Y PLOT" is punched in columns 3 through 10 .

(15-38) —— Arbitrary 24-character title for the horizontal axis.

Card 2 :

E8.0	E8.0	E8.0
LENX	XMIN	XMAX

(1-8) —— Variable "LENX" , the length of the horizontal ("X") axis, in inches. Zero or blank is defaulted to eight (8.0) inches.

(9-16) —— Variable "XMIN" , the minimum "X" value (value at left end of horizontal axis).

(17-24) —— Variable "XMAX" , the maximum "X" value (value at the right end of the horizontal axis).

Note : If the user leaves both "XMIN" and "XMAX" blank, the EMTP will automatically choose these values to cover the curve being plotted (by means of call to CalComp "SCALE").

Card 3 :

E8.0	E8.0	E8.0	E8.0	E8.0
LENY	YMIN	YMAX	DIV	SYM

(1-24) —— Variables "LENY" , "YMIN" , and "YMAX" , which are analogous to the X-axis variables of Card 2 —— only here parameters are for the vertical ("Y") axis.

(25-32) DIV —— Number of divisions per inch of the graph paper which is being used. This is used as a parameter for CalComp routine "[illegible]" . A zero or blank field is defaulted to ten (10.0).

(33-40) SYM —— One less than the number of symbols which is used to identify the curves. Zero or blank is interpreted to mean that no symbols shall be placed on the curves for purposes of identification. Standard CalComp identification symbols are used, based on the curve number.

Rule 3 : The above cards are to be followed by a conventional EMTP plot-specification card (see page 40d of the User's Manual). Some fields are ignored, however, and others have an altered meaning. Supply the following information:

(1-2)	Punch "1" in column 2, always.
(3)	Graph type code. Use "4" for node voltages, "8" for branch voltages, and "9" for branch currents.
(4)	A code-integer for the units of the column 8-15 time specification. Use "4" for milliseconds, etc., as with conventional plots.
(8-11)	Minimum or beginning time of the points to be plotted, in units of the column-4 specification.
(12-15)	Maximum or ending time of the points to be plotted, in units of the column-4 specification.
(25-30) (31-36) (37-42) (43-48)	Six-character names (A6 format) of EMTP variables which are to be plotted. The first two variables are for one curve, as an ordered (X,Y) pair of variables. For node voltages, then, columns 25-36 identify the first curve (with the X-name appearing first), and columns 37-48 identify the second (if a second exists). For branch voltages or branch currents, pair of names is required for variable identification, recall (e.g., columns 25-36 just for the X-variable); for more than one curve of branch variables, the "BRANCH" option can be used (see Point 4 , page 40g of the User's Manual).

As an example of "X-Y PLOT" usage, see the plot at the top of page 8 , on the left. The data cards which were read by overlay-31 plotting to produce this plot are listed as follows:

```
PRINT HEAD OFF
2TEST OF TYPE-96  PSEUDO-NONLINEAR HYSTERETIC REACTANCE ELEMENT.
 FLUX VS. CURRENT HYSTERESIS PLOT OF NED AND JIN'S TYPE-96 PSEUDO-NONLINEAR
 ELEMENT.   SINUSOIDAL DRIVING VOLTAGE IS USED.
 X-Y PLOT    TYPE-96 CURRENT IN AMPS
      5.0       -4.      4.8
      6.8       -1.7     1.3             8.8
194     8.8 25.              TACS  CURR  TACS  FLUX  HYSTERESIS GRAPHFLUX IN VOLT-SEC
```

Should the user want to switch back to conventional plotting after he is done with his X-Y PLOT usage, a simple trick is required. Repeat the three cards of the request which switched to X-Y PLOT usage in the first place, only with LENX = 9999. This is taken as a special flag meaning that a return to conventional (vs. time) plotting is desired.

In order for the Y-axis labeling (numbers) of a printer plot to be correct, LENY = 13.0 is required. For any other Y-axis length, the user should disregard the Y-axis numbers of a printer plot of the X-Y PLOT type. The curve itself should be validly constructed according to the user's requested axis scaling, however.

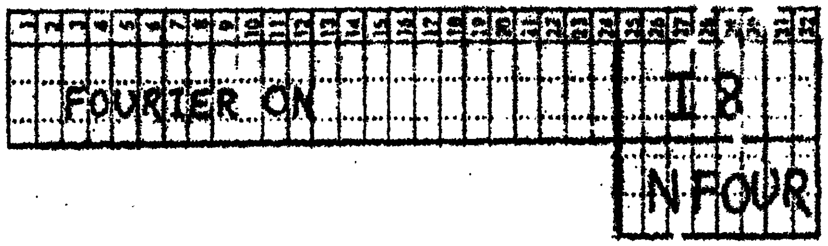
Extra working space is required for X-Y printer plots, beyond that needed for conventional (time) plots. This is invisible, and neither affects the user nor the computer (no additional arrays were added to the EMTP), as long as sufficient working space remains. Variable dimensioning (see Section 0.6) is the key determiner, in that it fixes the size of working space COMMON /C31B01/ KARRAY(?????) according to the total size of /LABEL/ , plus (usually minus) any additional user-requested offset. This same working space is used for building the X-Y PLOT image from the raw data points of the curves in question. For 130 cells of resolution in both directions, 16900 INTEGER cells of extra storage are required (in addition to space to store the raw data points for the curve or curves). If sufficient working space for such an image is not available, there will be a non-fatal error message, and the plot card will simply be skipped.

The "X-Y PLOT" option is available for both printer plots and CalComp plots, in any combination. But when using both via the "CALCOMP PRINTER" request, many users will have a conflict between the 13-inch wide printer output (131 columns at 10 columns/inch) and their narrower plotter (our BPA Versatek is 11 inches). There is trouble with the Y-axis length, which runs across the paper of both devices. If a CalComp plot was really desired, the upper quarter of it should not be lost off the upper edge of the paper, so LENY, YMIN, and YMAX should be selected to fit this smaller width. The printer plot will still be produced, and according to this requested scale. But the user should be warned that the Y-axis and its marking will be erroneous. Logic for printing and putting numbers on the Y-axis was fixed for 131 column output back in the year one (1975?), and is not now (September, 1980) being altered to accomodate this special case. Hence, if X-Y plotting in the "CALCOMP PRINTER" mode is used, and if the Y-axis length does not correspond to the full line printer width, the printed Y-axis will be erroneous, and should be ignored.

As for the resolution in each direction (number of cells/inch), for a printer plot, this is under user control. Recall that variable LNPIN gives the number of printer lines per inch; while it should be automatically defined according to local usage (in module "SYSDEP" of overlay 1), it can be altered by the user as per Section 1.0c . As for the number of characters/inch across a printed line, this is nominally set at 10, corresponding to conventional older printers. If the X-Y PLOT user really wants to redefine it, however, he can do so via a sixth field (cols. 41-48) on the Y-axis card. This extra field is also E8.0 information. But such an over-ride will not affect the Y-axis and its labeling, which has 10 built into it. If the user over-rides the 10 characters/inch, then, he should ignore the numbers on the printed Y-axis.

Point 16 : Card for Fourier series computation

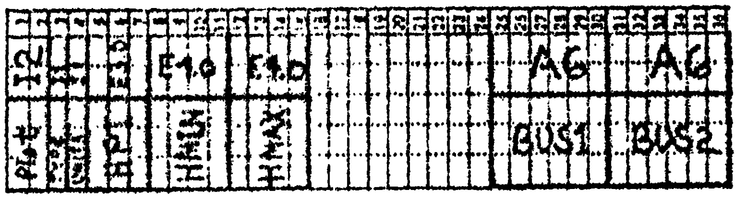
Although it has nothing to do with plotting, the Fourier series computation of the EMTP can only be accessed via this EMTP data classification, using the special request card (see right) which switches from plotting to Fourier series:



(3-12) ---- special request word "FOURIER ON"

(25-32) ---- Number of harmonics which are to be printed, NFOUR . If left blank, 30 will be printed (default value). For KPL equidistant points in the fundamental period, only KPL/2 harmonics are computed. If the user punches a larger NFOUR , it will automatically be reduced to this maximum.

Next come "plot cards", each of which identifies one EMTP variable and a time window over which the Fourier analysis is to be performed. Columns 16-24 and 37-80 can be left blank. Punch only:



(1- 2) ---- Punch a "1" in column 2, as with all plot cards.

(3) ---- Punch "4", "8", or "9", depending upon whether one is to Fourier analyze a node voltage, a branch voltage, or a branch current, respectively.

(4) ---- A code number indicating which units are desired for time parameters HPI, HMIN, and HMAX below. For cycles at the power frequency, punch "2"; etc.

(5- 7) ---- Punch any believable horizontal scale HPI . This data is not used for the Fourier calculation, but a credable value is required to successfully pass through plot card data checking logic.

(8-11) ---- The beginning time "HMIN" of the one-cycle window that is to be used for the Fourier analysis, in units of whatever the user has selected by his punch of column number 4.

(12-15) ---- The ending time "HMAX" of the one-cycle window, etc.

(25-30) ---- "BUS1" , first A6 EMTP variable name.
(31-36) "BUS2" , 2nd A6 EMTP variable name, if any. For the Fourier analysis of a node voltage, only BUS1 is used; but for branch voltage or current, BUS2 is also required to identify the variable.

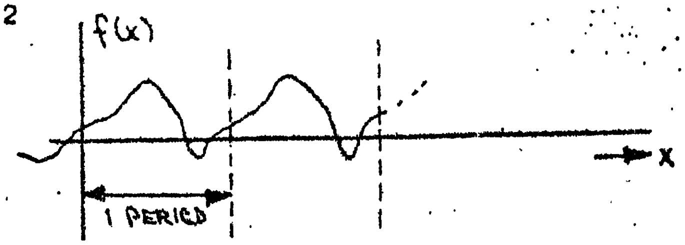
There are as many such "plot cards" as the user wants Fourier analyses. For each, there will be a tabulated output showing the harmonic number (first column), cosine coefficient (2nd column), sine coefficient (3rd column), complex amplitude (4th column), and relative size (fifth column), of which the following is an example:

```
  ROMAGNETIC TRANSIENTS PROGRAM (EMTP), DIGITAL (DEC) VAX-11/780 TRANSLATION AS USED BY BPA IN PO
 ATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS.)= 09/30/80  22.54.40      VAX/VMS PLOT FILE = 910225140.PL
FOR INFORMATION, CONSULT THE 700-PAGE EMTP RULE BOOK DATED SEPTEMBER, 1980.   PROGRAM VERSION = "M2
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF   /LABEL/   EQUALS 249871  INTEGER WORDS.
   125  6100 10000     50    300    100    140     20  9000    400      9      4    30  6000 27500   120
------------------------------------------------------------1----------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA 1 INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COL
                                                  0         1         2         3         4
                                                  0         0         0         0         0
------------------------------------------------------------1----------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.              1BEGIN NEW DATA CASE
MISC. DATA.    0.100E+01    0.900E+01   0.000E+00  1       1.0       9.0
MISC. DATA.     1      1  0   0   0   0   0   0   0   0  1        1         1
SERIES R-L-C.      0.100E+01  0.000E+00  0.000E+00  1  VALUE                           1.0
BLANK CARD TERMINATING BRANCH CARDS.               1BLANK CARD ENDING BRANCH CARDS.
BLANK CARD TERMINATING SWITCH CARDS.               1BLANK CARD ENDING SWITCH CARDS.
SOURCE.     0.00E+00  0.00E+00   0.00E+00  0.00E+00 1 1VALUE
BLANK CARD TERMINATING SOURCE CARDS.               1BLANK CARD ENDING SOURCE CARDS.
REQUEST FOR OUTPUT OF ALL NODE VOLTAGES.           1 1

COLUMN HEADINGS FOR THE   1  EMTP OUTPUT VARIABLES FOLLOW.   THESE ARE ORDERED ACCORDING TO THE FIVE
POSSIBLE EMTP OUTPUT-VARIABLE CLASSES, AS FOLLOWS ....
  FIRST    1  OUTPUT VARIABLES ARE ELECTRIC-NETWORK NODE VOLTAGES (WITH RESPECT TO LOCAL GROUND)1
   NEXT    0  OUTPUT VARIABLES ARE BRANCH VOLTAGES (VOLTAGE OF UPPER NODE MINUS VOLTAGE OF LOWER NODE
   NEXT    0  OUTPUT VARIABLES ARE BRANCH CURRENTS (FLOWING FROM THE UPPER EMTP NODE TO THE LOWER)1.
   NEXT    0  OUTPUT VARIABLES PERTAIN TO DYNAMIC SYNCHRONOUS MACHINES, WITH NAMES GENERATED INTERNAL
  FINAL    0  OUTPUT VARIABLES BELONG TO  'TACS'  (NOTE INTERNALLY-ADDED UPPER NAME OF PAIR).
BRANCH POWER  CONSUMPTION (POWER  FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH VOLTAGE FOR THIS GROUP
BRANCH ENERGY CONSUMPTION (ENERGY FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH CURRENT FOR THIS GROUP

 STEP     TIME        VALUE

    0 0.000000 0.000000E+00
ANOTHER INPUT CARD FOR TYPE 1-10 SOURCES.            1      3.4
    1 0.100E+01 0.340000E+01
ANOTHER INPUT CARD FOR TYPE 1-10 SOURCES.            1.8485282
    2 0.200E+01 0.848528E+00
ANOTHER INPUT CARD FOR TYPE 1-10 SOURCES.            1      0.0
    3 0.300E+01 0.000000E+00
ANOTHER INPUT CARD FOR TYPE 1-10 SOURCES.            1-.434314
    4 0.400E+01-0.434314E+00
ANOTHER INPUT CARD FOR TYPE 1-10 SOURCES.            1      -.2
    5 0.500E+01-0.200000E+00
ANOTHER INPUT CARD FOR TYPE 1-10 SOURCES.            1-.848528
    6 0.600E+01-0.848528E+00
ANOTHER INPUT CARD FOR TYPE 1-10 SOURCES.            1      -.4
    7 0.700E+01-0.400000E+00
ANOTHER INPUT CARD FOR TYPE 1-10 SOURCES.            1-1.56569
    8 0.800E+01-0.156569E+01
ANOTHER INPUT CARD FOR TYPE 1-10 SOURCES.            1      1.0

COMMENT CARD.                                      1C 34567890123456789012345678901 2
FOURIER SERIES STARTED.  NFOUR =       10          1  FOURIER ON                      10
** PLOT CARD.    0.100E+01  0.100E+01  0.800E+01   1 143 1. 1.0 8.0          VALUE

BEGIN FOURIER SERIES CALCULATION USING       8   EQUIDISTANT POINTS.   BEGINNING TWO POINTS =
   0.3400000000E+01     0.8485282000E+00          ENDING TWO POINTS =   -0.4000000000E+00   -0.1565690

COEFFICIENTS OF RESULTANT FOURIER SERIES, WITH  "COMPLEX AMPLITUDE"  BEING THE SQUARE ROOT
OF THE SUM OF THE SQUARES OF THE TWO PRECEDING ENTRIES.   THE FINAL COLUMN APPLIES TO THIS AMPLITUDE
 HARMONIC          COSINE                   SINE                 COMPLEX              FRACTION OF
  NUMBER         COEFFICIENT             COEFFICIENT            AMPLITUDE             FUNDAMENTAL
       0      0.9999952500E-01      0.0000000000E+00      0.9999952500E-01          0.08574991
       1      0.9999990764E+00      0.6000008972E+00      0.1166190047E+01          1.00000000
       2      0.9000000000E+00      0.5000010560E+00      0.1029563524E+01          0.88284369
       3      0.8000009236E+00      0.4000008972E+00      0.8944284184E+00          0.76696626
       4      0.6000004750E+00      0.0000000000E+00      0.6000004750E+00          0.51449631


BLANK CARD TERMINATING PLOT SPEC. CARDS.          1BLANK CARD ENDING PLOT CARDS.
```

FOURIER ANALYSIS PROGRAM

Ref: Mathematical Methods for Digital Computers, edited by A. Ralston & H. S. Wilf, John Wiley & Sons, New York 1960. Paper by G. Goertzel: Fourier Analysis, page 258-262

Given a periodic function f(x):



This periodic function can be expressed as a series of trigonometric functions

$$f(x) = \sum_{i=0}^{\infty} a_i \cos(ix) + \sum_{i=0}^{\infty} b_i \sin(ix) \qquad (1)$$

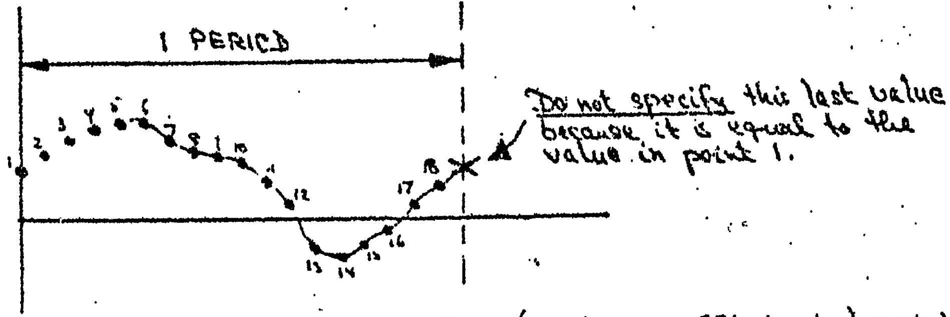
with a_0 = dc offset,

$\sqrt{a_1^2 + b_1^2}$ = amplitude of fundamental frequency, and

$\sqrt{a_i^2 + b_i^2}$ = amplitude of i-th harmonic.

How to Use the Program

Define the curve within one period by n points at equal distances along x($n \geq 2$):



Do not specify this last value because it is equal to the value in point 1.

The program will compute the values a_0, ... a_m (cosine-coefficients) and b_0, ... b_m (sine-coefficients) of Eq. (1), as well as the magnitudes $C_0, \ldots C_m$, with

$$C_i = \sqrt{a_i^2 + b_i^2} \qquad (2)$$

If n is even, then $m = \frac{n}{2}$, (3a)

if n is odd, then $m = \frac{n-1}{2}$. (3b)

The resulting finite series

$$F(x) = \sum_{i=0}^{m} a_i \cdot \cos(ix) + \sum_{i=0}^{m} b_i \cdot \sin(ix) \qquad (4)$$

passes through the n given points ("exactly," except for round-off errors) and provides a smooth interpolation between points with the least possible number of harmonics.

The sample usage just displayed is based on Hermann's 8-point illustration in the documentation which follows. A user-defined Type-1 EMTP source was employed to establish the eight desired data points as node voltages for node VALUE . Due to the EMTP field width of eight, precision is slightly reduced, note.

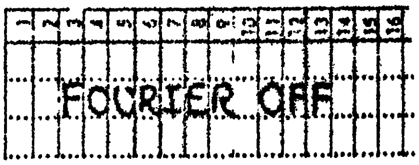
The user is reminded of the importance of defining exactly one cycle of the periodic wave, with no overlap. Because of the floating-point counting of the EMTP (T = T + DELTAT), this can be tricky, and even installation-dependent. The first two points and the last two points are printed out as confirmation, so that the user knows that his window is exactly right. In this regard, all plot points for T .LT. HMIN or T .GT. HMAX are rejected. If the user is having trouble with one or both end points, he may want to add or subtract half a time step when he defines HMIN and HMAX; and if this requires more field width than the regular format allows, remember the extended (16-column) precision option of Point 5 plot data.

The user is also warned that no interpolation on the EMTP plot file points is performed. Hence it is important that time-step size DELTAT (as defined on the floating-point miscellaneous data card) be an exact multiple of the period. For 50 Hz problems, this will usually be the case, but not so for we North American users of 60 Hz systems. Remember, if DELTAT = 1.E-4 sec, then there are exactly 166.666666.... steps in a cycle, which implies some error in the Fourier transformation. Better to choose DELTAT so that the number of steps per cycle is an integer. For 60 Hz systems, carry quite a bit of precision, preferably using free-format capability for the floating-point miscellaneous data card. Put several extra commas at the end of the nonzero data, so ensure proper bounding.

One final point regarding the FORTRAN, which is module "SERIES" of overlay 31. An interactive debugger can stop at S.N. 3209 and examine and or adjust various variables. (EVDOUB(J), J=1, KPL) is the data being transformed, and IPRSUP .GE. 3 will print it all.

Point 17 : Card to turn off Fourier Analysis, and return to plotting.

If the user wants to return to conventional EMTP plotting after the use of Point 16 Fourier transformation, this is possible. The switch back to the normal plotting mode is made via the "FOURIER OFF" request as shown at the right.



FOURIER OFF

BACKGROUND AND DOCUMENTATION OF EMTP FOURIER SERIES COMPUTATION

The Point 16 and Point 17 features were implemented very hurriedly by WSM on September 29th and 30th, 1980, just as this manual was going to press. It was a rush job, in response to Bob Hasibar's immediate need. Hermann had written a little self-contained Fourier analysis program many years ago, and it is his coding which formed the basis of the new EMTP feature. The first three pages of Hermann's five-page writeup dated 30 October 1972 are reproduced below as added documentation of the formulas used:

432 401

No longer applicable

Form of Data Deck

Any number of curves can be analyzed consecutively. Each curve is specified with

one card defining	n	Format I3
as many cards as necessary defining	$f_1, f_2, f_3, f_4, f_5, f_6$ $f_7, \ldots \qquad f_{12}$	Format 6F12.7

Terminate the data deck with a blank card.

Test Examples

Example A: The function

$$f(x) = 0.1 + \cos x + 0.9\cos 2x + 0.8\cos 3x + 0.6\cos 4x + 0.6\sin x + 0.5\sin 2x + 0.4\sin 3x + 0.8\sin 4x$$

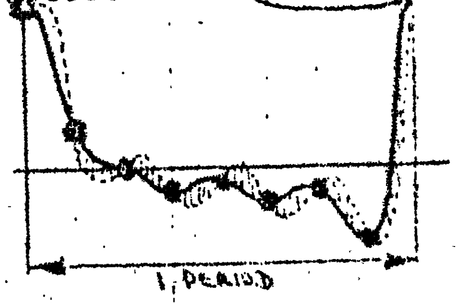
was used to generate 8, 9 and 20 values at equidistant points to define one period of the periodic function. These points were used as input to generate the coefficients, which agreed with those of the original function as shown on p. 3.

Example B: The curve was taken from a study described in E. J. Dolan, D. A. Gillies, and E. W. Kimbark, "Ferroresonance in a Transformer Switched with an EHV Line," IEEE Trans. on Power Apparatus and Systems, Vol. PAS-91, May/June 1972, pp. 1273-1280. The curve as well as the results are shown on p. 4-5.

Example A. Results

H. W. Dommel
10/30/72

```
FOURIER ANALYSIS

RECORD OF ORDINATES IN   8 EQUIDISTANT POINTS
    3.3999999    .8485282  -0.0000000    -.4343144    -.2000000    -.8485281
   -.3999999  -1.5655856

FOURIER COEFFICIENTS
HARMONIC       COS-COEFF.       SIN-COEFF.       MAGNITUDE
    0            .100000         0.000000         .100000
    1           1.000000          .600000        1.166190
    2            .900000          .500000        1.029563
    3            .800000          .400000         .894427
    4            .600000         0.000000         .600000
```



With 8 points given, the sine term of the 4th harmonic can no longer be recognized (it could be anything; see dashed line at left). Therefore, it is set to zero.

43m

```
FOURIER ANALYSIS

RECORD OF ORDINATES IN  9 EQUIDISTANT POINTS
                                                  .4294230  -1.0036614   .1115541
    3.3999999   1.5956150   -.6111941
   -1.1294229   -.4137808  -1.4333908

FOURIER COEFFICIENTS
HARMONIC      COS-COEFF.       SIN-COEFF.       MAGNITUDE
   0           .100000          0.000000         .100000
   1          1.000000          -.600000        1.166190
   2           .900000           .500000        1.029563
   3           .800000           .400000         .894427
   4           .600000           .800000        1.000000

FOURIER ANALYSIS

RECORD OF ORDINATES IN  20 EQUIDISTANT POINTS
                                                  -.2222683   -.9123145   -.0000001
    3.3999999   3.9985650   2.1335587
     .6979639    .1132515   -.6517609   -.9534801   -.2000001    .1379110
    -.4564355  -1.0941824   -.9059809   -.3999999   -.6494687  -1.4509024
   -1.2243422    .6718544

FOURIER COEFFICIENTS
HARMONIC      COS-COEFF.       SIN-COEFF.       MAGNITUDE
   0           .100000          0.000000         .100000
   1          1.000000           .500000        1.166190
   2           .900000           .500000        1.029563
   3           .800000           .400000         .894427
   4           .600000           .800000        1.000000
   5           .000000           .000000         .000000
   6           .000000           .000000         .000000
   7           .000000          -.000000         .000000
   8           .000000          -.000000         .000000
   9           .000000          -.000000         .000000
  10           .000000          0.000000         .000000
```

Point 18 : Card to mark termination of all plot cards

A blank card is used to signal the end of all data cards associated with plotting. This then also completes the data for the data case being set up (see Section 1.).

2. DESCRIPTION OF TRANSIENTS PROGRAM OUTPUT

This chapter is designed to aid the user in interpreting the printed (and plotted) output produced by the Transients Program.

2.1 Input Data Listing

So as to completely document all data, a listing of all input cards is provided as part of the printed output:

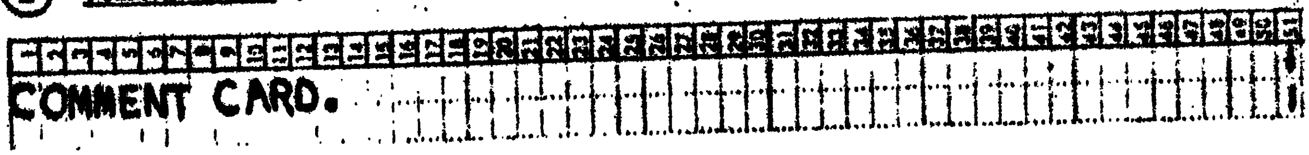
1. All 80 columns are printed, character by character, in columns 52 through 131 of the paper.
2. The character "1" is printed in column 51 of the line, to mark the beginning of the card image.
3. Columns 1 through 50 of the line are reserved for interpretation of the input card in question. See below for a tabulation of what is printed out for different types of data cards.
4. There is only one line of printing for each data card read; no spill-over to extra lines is allowed, for aesthetic reasons.

See the sample program output of Section 2.3 for an illustration of these rules.

As not all data cards are inputted at once, "breaks" in the above card-listing will occur, with other program printout appearing in between. Yet all data from the case control card through the source cards (see Point a of Section 1., data classes 1 through 5) will appear listed contiguously —— which is the most important range of interest, covering the entire network description.

The interpretation accompanying each different type of input card can be decoded using the following explanations.

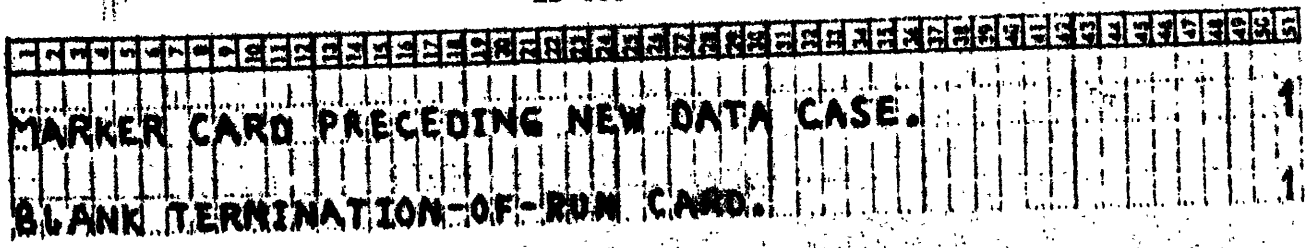
① Comment Card (Section 1.)



```
COMMENT CARD.                                     1
```

② Cards to Begin a New Data Case (Section 1.0)

First, there are the two different cards which are associated with separating different data cases, or stopping execution of the EMTP (see Sections 1.0a , 1.0b). Of the two interpretations shown below, the first is for a "BEGIN NEW DATA CASE" card, the second is for the blank card which turns the EMTP off.



```
MARKER CARD PRECEDING NEW DATA CASE.              1
BLANK TERMINATION-OF-RUN CARD.                    1
```

Section 1.0c shows how the user can re-define built-in program parameters "LNPIN" , "SZPLT" , "NSMTH" , "EPSILN" , "KPARTB" , and "STATFR" . Interpretation for these special request records is as follows:

NEW PRINTER SPACING, LINES/DISTANCE = I8
LNPIN

NEW PLOTTER PAPER-HEIGHT LIMIT. E13.3
SZPLT

CHANGE SUCCESSIVE OSCILLATION LIMIT. I8
NSMTH

MISC. DATA CONSTANT "EPSILN" . E12.3
EPSILN

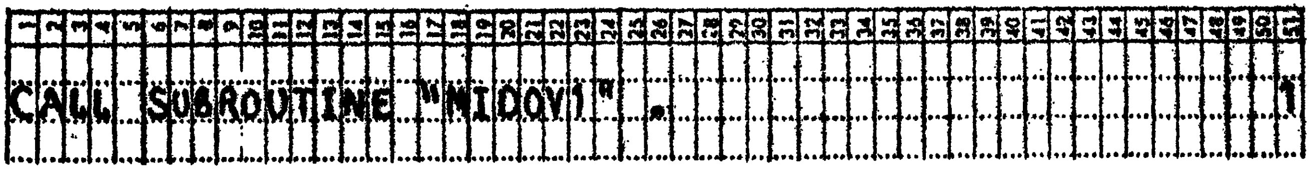
EXPONENT OF HIGH RESISTANCE. R = E12.2
10^{KPARTB}

REDEFINED POWER FREQUENCY = E12.3 HZ.
STATFR

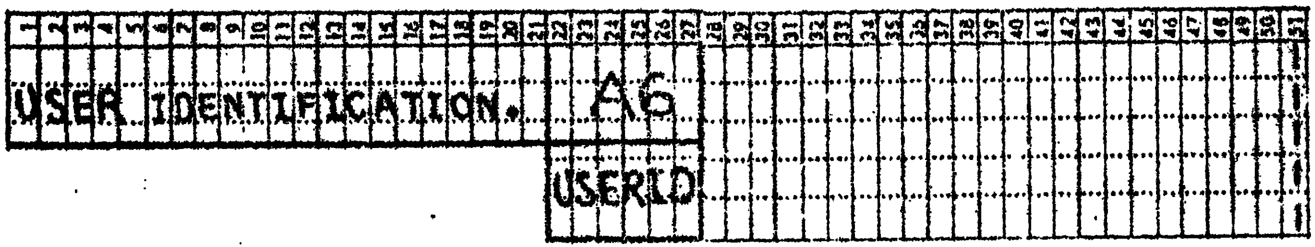
Section 1.0d explains usage of the "REPLOT" feature, the leading request card for which is interpreted as follows:

REQUEST TO RE-PLOT OLD PLOT DATA. 1

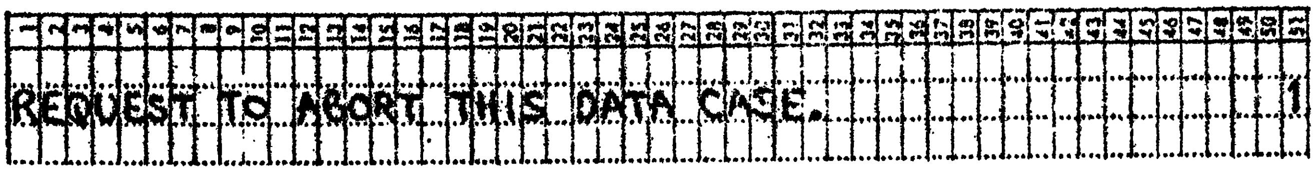
Section 1.0e explains how installation-dependent module "MIDOV1" of overlay number one can be called on demand by the user. Interpretation of the special request record reading "FILE REQUEST" is as follows:



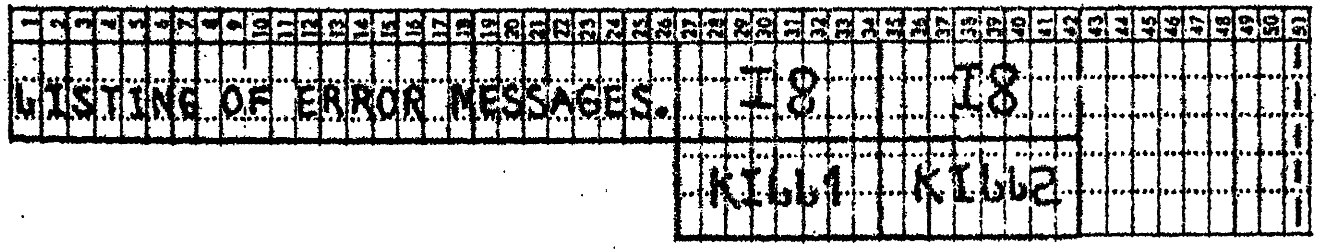
Section 1.0e1 explains how six-character alphanumeric identification of the user can be specified, principally for purposes of EMTP plot identification. Interpretation of the special request record reading "USER IDENTIFICATION" is as follows:



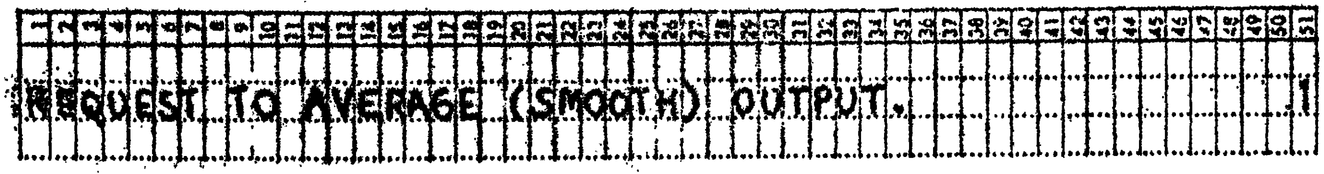
Section 1.0e2 explains how to disable the execution of an EMTP data case (one of several to be solved). Interpretation of the special request record reading "ABORT DATA CASE" is as follows:



Section 1.0e3 explains how to print a range of EMTP error messages (KILL codes, beginning with KILL1 and continuing through KILL2). Interpretation of the special request record reading "KILL CODES" is:



Section 1.0e4 explains how the EMTP output vectors can be averaged over successive time steps. Interpretation of the special request record reading "AVERAGE OUTPUT" is as follows:



Section 1.0e5 explains how the total TACS working space of List 19 can be allocated among the 15 different TACS tables. First, there is interpretation for the three "ABSOLUTE TACS DIMENSIONS" cards:

SET ABSOLUTE TACS LIST SIZE LIMITS.			
1ST TACS DIMENSIONS CARD.	I6	I6	I6
	LT1	LT2	LT3
2ND TACS DIMENSIONS CARD.	I6	I6	I6
	LT11	LT12	LT13

Second, there is interpretation for the three data cards associated with the special request record "RELATIVE TACS DIMENSIONS" :

PROPORTIONAL ALLOCATION OF TOTAL TACS STORAGE.			
RELATIVE LIST SIZES.	E9.2	E9.2	E9.2
	F1	F2	F3
RELATIVE LIST SIZES.	E9.2	E9.2	E9.2
	F11	F12	F13

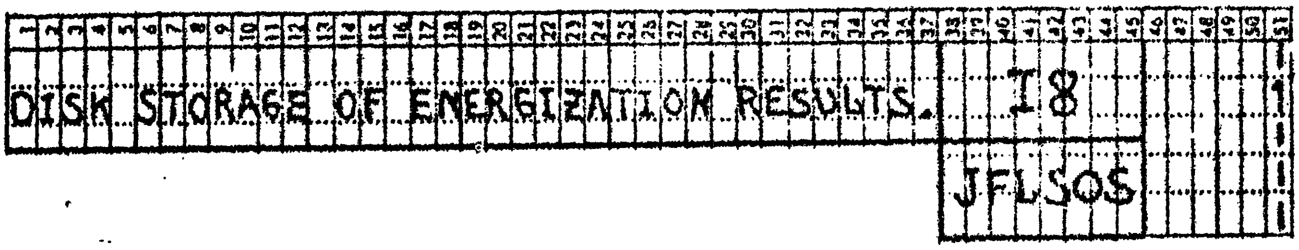
Section 1.0e6 explains how the results of two or more "STATISTICS" solutions can be combined for purposes of overvoltage tabulation. First, there is interpretation for the special request record which reads "TABULATE ENERGIZATION RESULTS" :

REQUEST FOR "STATISTICS" TERMINATION.	1

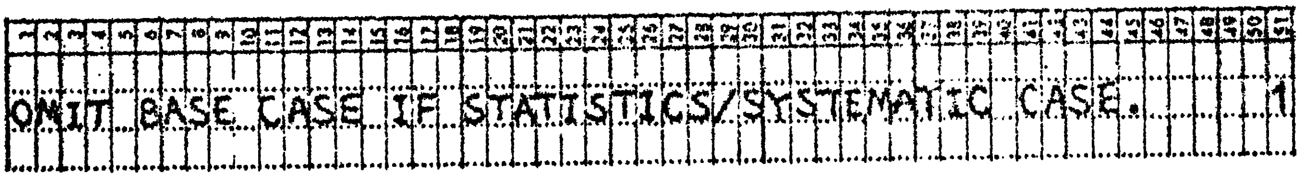
Next comes interpretation for the one or more data cards which give the integers that characterize the data files in question:

FILE NAMES.	I4	I4	I4	I4	I4	I4	I4	I4	I4
	JF_1	JF_2	JF_3	JF_4	JF_5	JF_6	JF_7	JF_8	JF_9

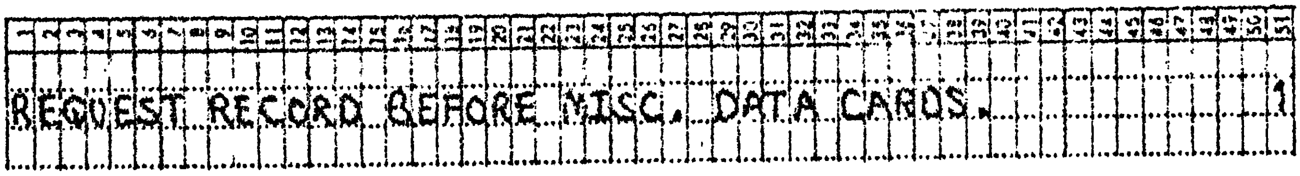
Section 1.0e7 explains how a "STATISTICS" simulation can be saved for later statistical tabulation, possibly in combination with other such partial solutions. Interpretation of the special request record reading "STATISTICS OUTPUT SALVAGE" is as follows:



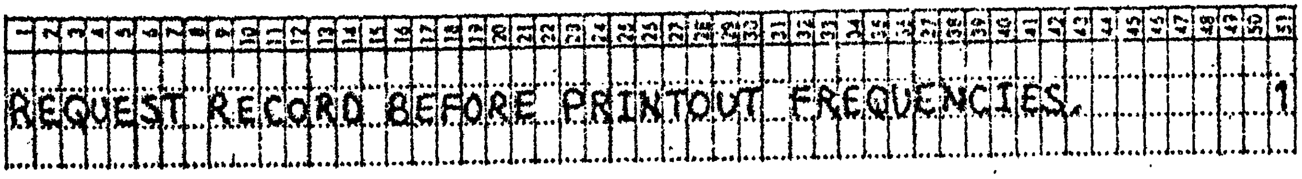
Section 1.0e8 explains how the user can omit running the base case solution of a "STATISTICS" or "SYSTEMATIC" data case. The special request record "OMIT BASE CASE" is interpreted as follows:



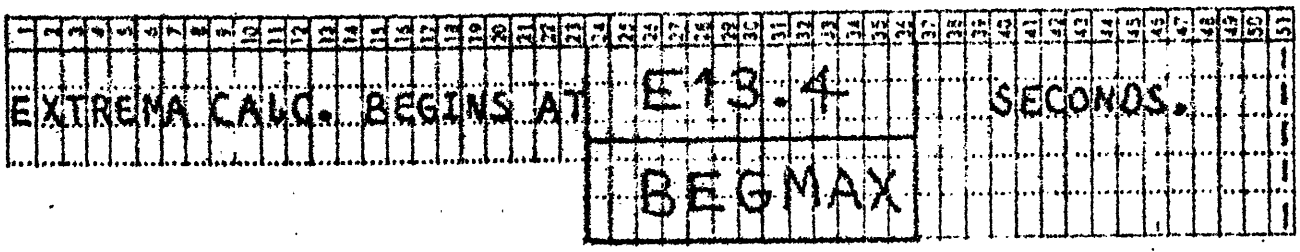
Section 1.0e9 explains how the user can have the familiar floating-point and integer miscellaneous data cards (see Section 1.0h) read. Interpretation of the miscellaneous data cards themselves, as well as any extensions, are as expected, so shall not be repeated here. It only remains for us to illustrate interpetation of the special request record reading "MISCELLANEOUS DATA CARDS" :



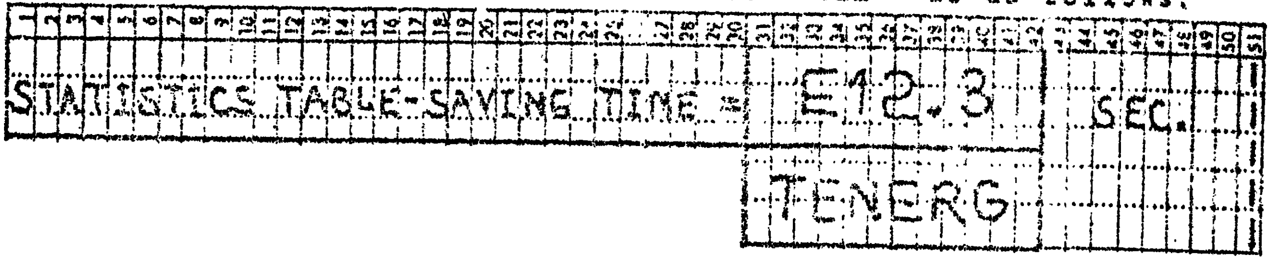
Section 1.0e10 explains how the user can request a special reading of th familiar data card which provides for variation of the time-step loop printout frequency (see Section 1.1b). Because the data card itself and its interpretation are unchanged, they shall not be repeated here. It only remains for us to illustrate interpretation of the special request record reading "CHANGE PRINTOUT FREQUENCY" :



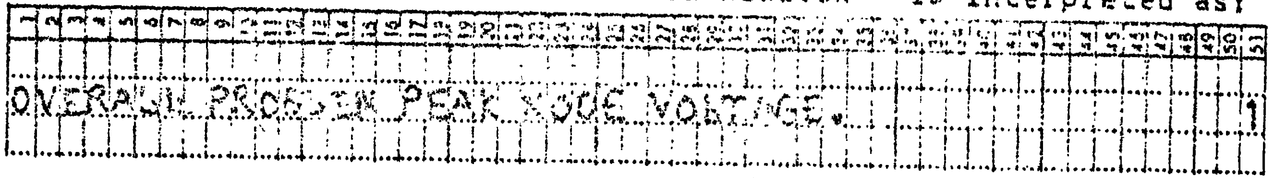
Section 1.0e11 explains how the user can manually define the time at which the search for extrema is to begin. Interpretation of the special r quest record reading "BEGIN PEAK VALUE SEARCH" is as follows:



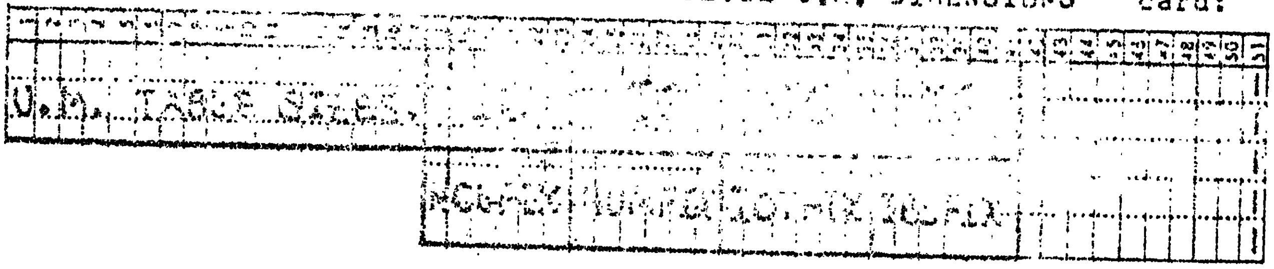
Section 1.0e12 explains how the user can define the table-saving time in the case of "STATISTICS" data cases. Interpretation of the special request record "TIME OF DICE ROLL" is as follows:



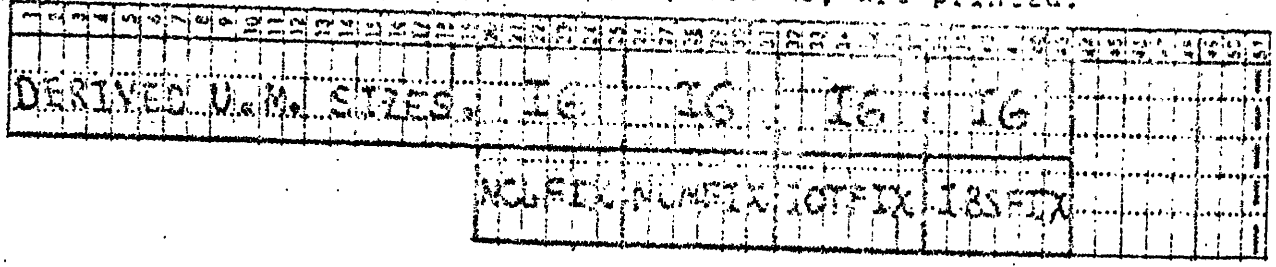
Section 1.0e13 explains how the user can request output of the peak node voltage for the entire network (peak over all nodes). The special request record "PEAK VOLTAGE MONITOR" is interpreted as:



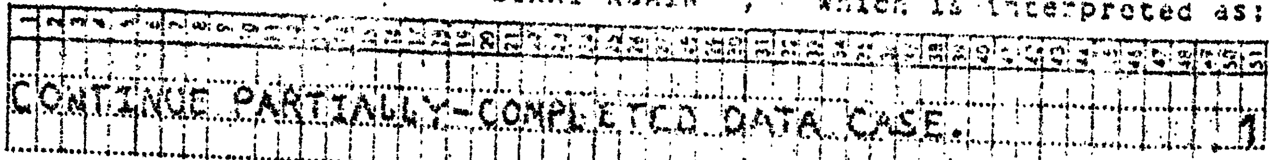
Section 1.0e14 explains how the total U.M. working space of List 25 can be allocated among the four different U.M. tables. First, there is interpretation of the "ABSOLUTE U.M. DIMENSIONS" card:



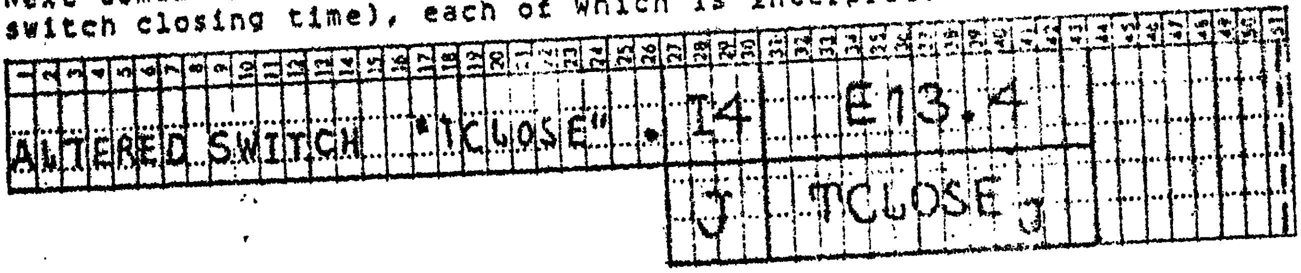
An alternative is provided by the special request "RELATIVE U.M. DIMENSIONS" , which is interpreted as follows. Note that the derived absolute sizes, not the proportions, are printed:



Section 1.0e15 explains how the user can restart a previously-halted simulation (which had MEMSAV = 1 flag set). There are several data cards associated with this operation. The first of these is the special request record "START AGAIN" , which is interpreted as:

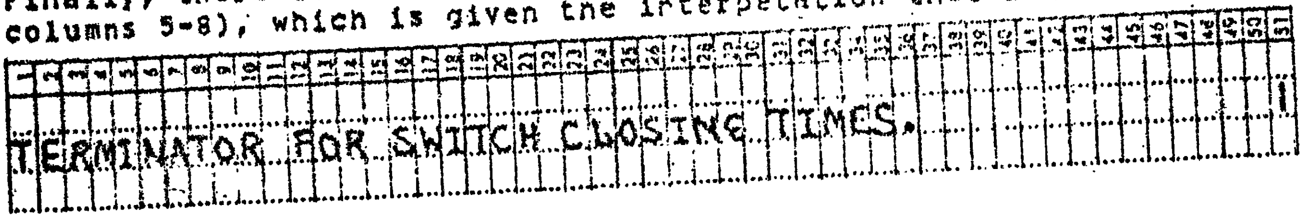


Next comes an indeterminate number of switch cards (switch number; ne switch closing time), each of which is interpreted as follows:



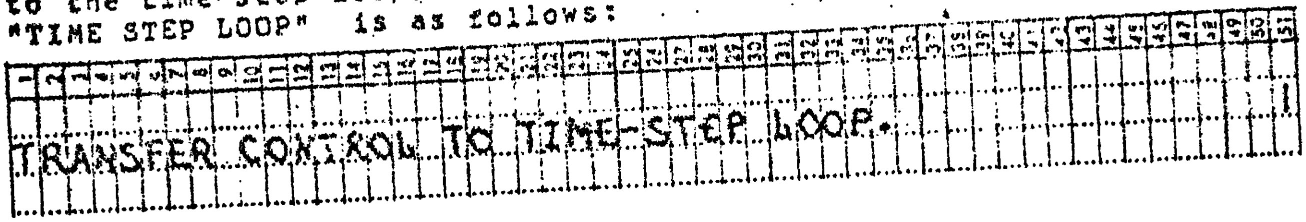
```
ALTERED SWITCH "TCLOSE" . I4  E13.4
                          J  TCLOSE J
```

Finally, there is the terminator for such cards ("9999" punched in columns 5-8), which is given the interpetation that follows:



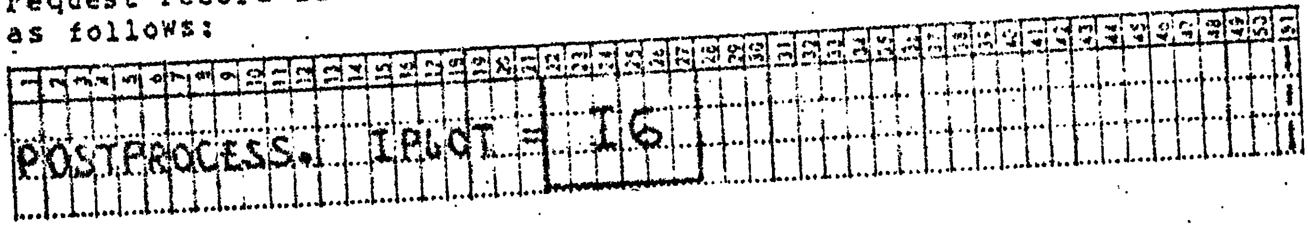
```
TERMINATOR FOR SWITCH CLOSING TIMES.
```

Section 1.0e16 explains how the user can transfer control directly to the time-step loop. Interpretation ot the special request record "TIME STEP LOOP" is as follows:



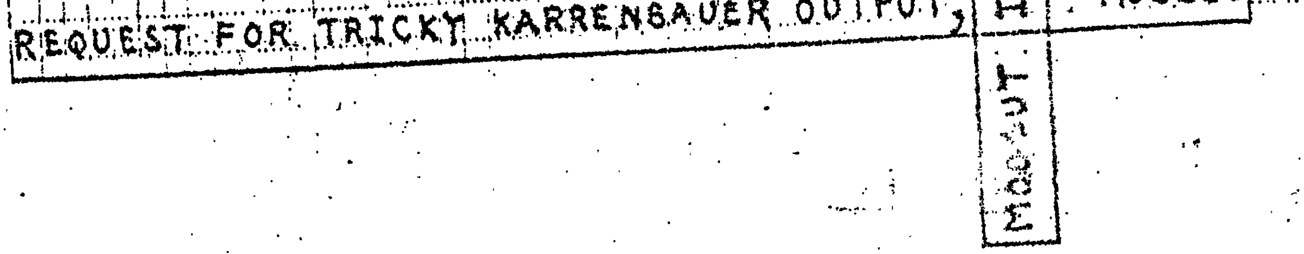
```
TRANSFER CONTROL TO TIME-STEP LOOP.
```

Section 1.0e17 explains how the user can postprocess an old plot file using TACS. This begins with an installation-dependent $-card ($OLDFILE), which shall not be documented here. But the key special request record is "POSTPROCESS PLOT FILE", which is interpreted as follows:



```
POSTPROCESS.  IPLOT = I6
```

Section 1.0f explains how Karrenbauer node voltage output can be requested to a single distributed line. Interpretation of this special request record is as follows:



```
REQUEST FOR TRICKY KARRENBAUER OUTPUT, I3 . MODES. 1
                                     MAXOUT
```

Section 1.0g shows how the user can request transfer to any of the auxiliary supporting programs which have been attached to the Transients Program proper. The different possible request records are interpreted as follows (for key words "XFORMER" , "SATURATION" , "WEIGHTING" , "LINE CONSTANTS" , "SEMLYEN SETUP" , "AMETANI SETUP" , and "CABLE CONSTANTS") :

REQUEST FOR TRANSFORMER IMPEDANCE-MATRIX ROUTINE	1
REQUEST FOR MAGNETIC-SATURATION ROUTINE.	1
REQUEST FOR WEIGHTING-FUNCTION ROUTINE.	1
REQUEST FOR LINE-CONSTANTS SUPPORTING PROG.	1
REQUEST FOR SEMLYEN STEP-RESPONSE ROUTINE.	1
REQUEST FOR AMETANI STEP-RESPONSE ROUTINE.	1
REQUEST FOR CABLE-CONSTANTS SUPPORTING PROGRAM	1
REQUEST FOR HAUER STEP-RESPONSE ROUTINE.	1

Section 1.0g1 explains that the intended control of Type 1-10 EMTP sources from FORTRAN subroutine "ANALYT" must be declared early, by means of a card bearing the key word "ANALYTIC SOURCES" . Interpretation of this special-request record is as follows:

REQUEST FOR USE OF ANALYTIC TYPE 1-10 SOURCES.	1

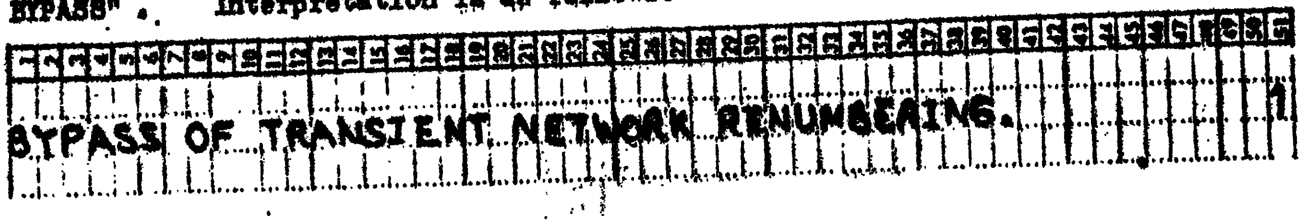
Section 1.0g2 explains that Type 1-10 EMTP sources can be controlled by TACS variables which are declared on a "TACS EMTP SOURCES" card. Interpretation of this special-request record is as follows:

TACS NAMES CONTROLLING TYPE 1-10 EMTP SOURCES.	1

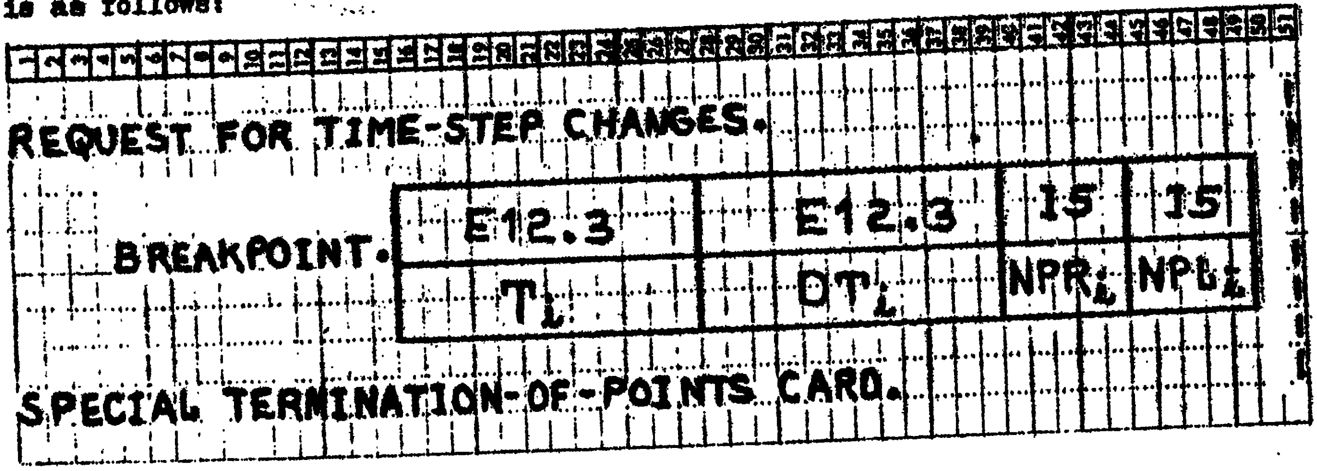
Section 1.0g3 explains that the EMTP will automatically loop over steady-state solutions of different frequencies, in response to a "FREQUENCY SCAN" card. Interpretation of this special-request record is as follows:

F-SCAN.	E12.3	E12.3	E12.3	I5	1
	f_{min}	Δf	f_{max}	NPD	

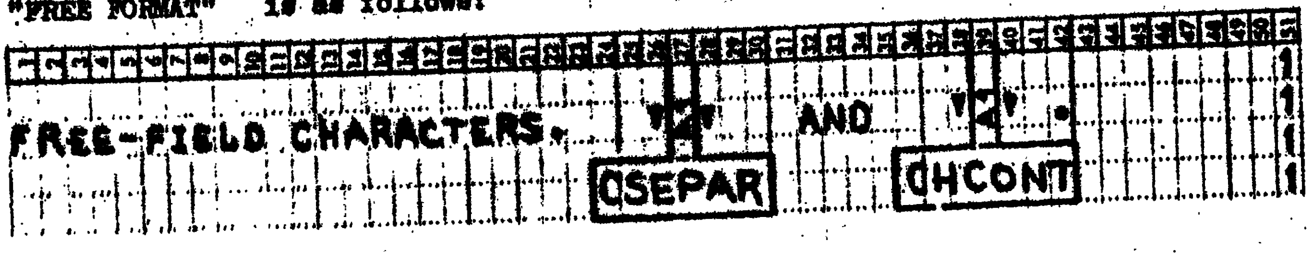
Section 1.0g4 explains that transient network node renumb ring can be bypassed by means of a special request card which bears the key-word text "RENUMBER BYPASS". Interpretation is as follows:



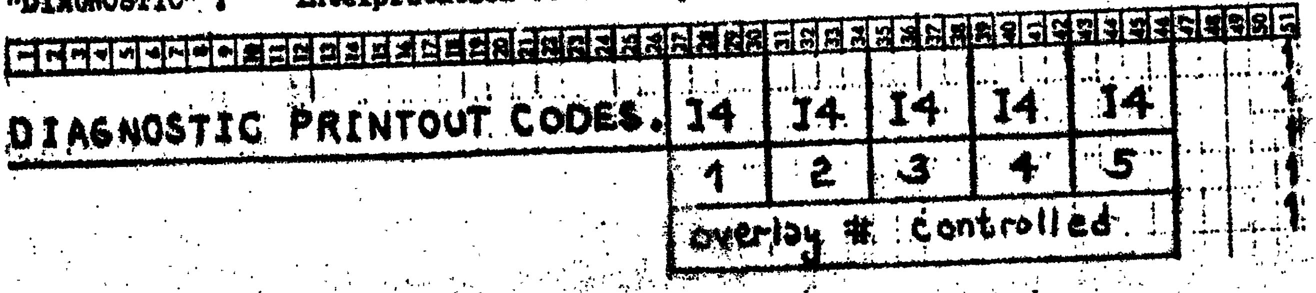
Section 1.0g5 explains that the time-step size "DELTAT" can be altered by the user at any point during an EMTP simulation. Three or more cards are required for such a specification. The first is a single special-request record which bears the key-word text "CHANGE DELTAT". Then come an indeterminate number of cards which define the time-instants T_i at which new step-sizes DT_i are to be applicable. Finally, the end of these is marked by a single card with "9999" punched in columns 13-16. Interpretation for these three classes of cards is as follows:


REQUEST FOR TIME-STEP CHANGES.
BREAKPOINT.
E12.3
E12.3
I5
I5
T_i
DT_i
NPR_i
NPL_i
SPECIAL TERMINATION-OF-POINTS CARD.

Se tion 1.0g6 provides for user-redefinition of the two characters which are used in conjunction with free-format data input. "CSEPAR" is the separator character between data fields, while "CHCONT" is the character which requests a continuation card. Interpretation of this special-request record which bears the key word "FREE FORMAT" is as follows:



Section 1.0g6 explains that EMTP diagnostic printout can be controlled selectively, overlay by overlay, using a card which bears the key-word text "DIAGNOSTIC". Interpretation of this special-request record is as follows:



The floating-point and integer miscellaneous data cards of Section 1.0h are interpreted as follows:

MISC. DATA.	E12.3	E12.3	E12.3
	Δt	T_{max}	XOPT

MISC. DATA	I5	I5	I3	I3	I3	I3	I3	I3	I3	I3
	IOUT	IPLOT	IDOUBL	KSSOUT	MAXOUT	IPUN	MEMSAV	ICAT	NENERG	IPRSUP

③ Specially-Requested Extensions to Misc. Data Cards (Section 1.1)

This class of data consists of cards which are only present in a data case if certain miscellaneous data parameters of Section 1.0h take on special, characteristic values.

For a "STATISTICS" or "SYSTEMATIC" data case, "NENERG" is punched nonzero (with absolute value equal to the number of energizations), and an extra statistical-overvoltage miscellaneous data card is appended, as per Section 1.1a . Interpretation of this record is as follows:

STATISTICS DATA.	I8	I8	I8	F9.4
	ISW	ITEST	IDIST	AINCR

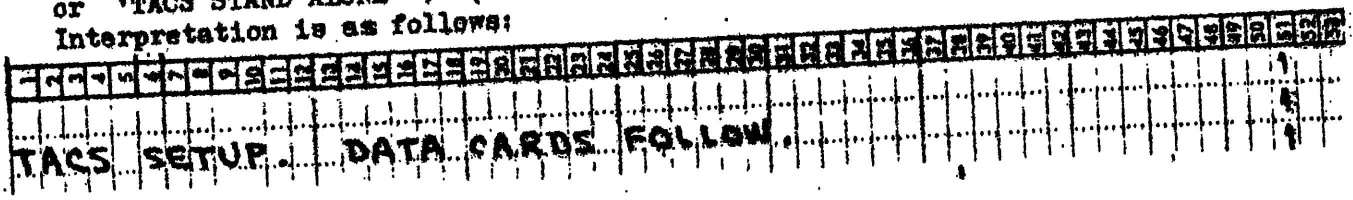
If the user wants to vary the printout frequency during the solution, "IPUN" is punched as -1 , and the special printout-frequency-change card of Section 1.1b is appended. Interpretation of this record is as follows:

PRINTOUT	I6	I6	I6	I6	I6	I6
	$KCHG_1$	$MULT_1$	$KCHG_2$	$MULT_2$	$KCHG_3$	$MULT_3$

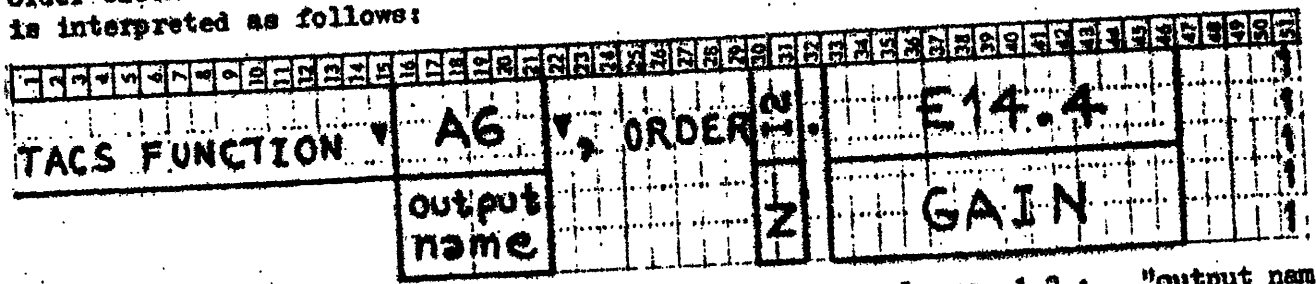
(3a) TACS Data

If a data case is to involve TACS modeling (see Section 8.), such data cards precede the first branch card (and follow the last extension (if any) to the miscellaneous data cards).

First comes a special-request card with the keyword 'TACS HYBRID' or 'TACS STAND ALONE' . (See Section 1.1d) Interpretation is as follows:

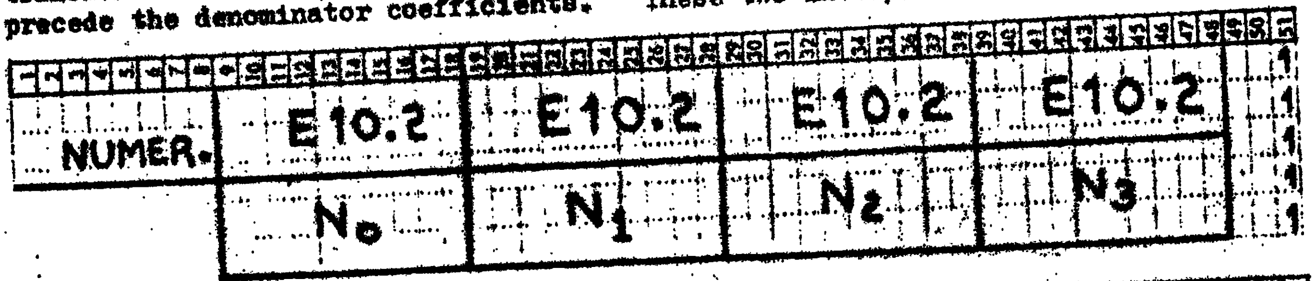

TACS SETUP. DATA CARDS FOLLOW.

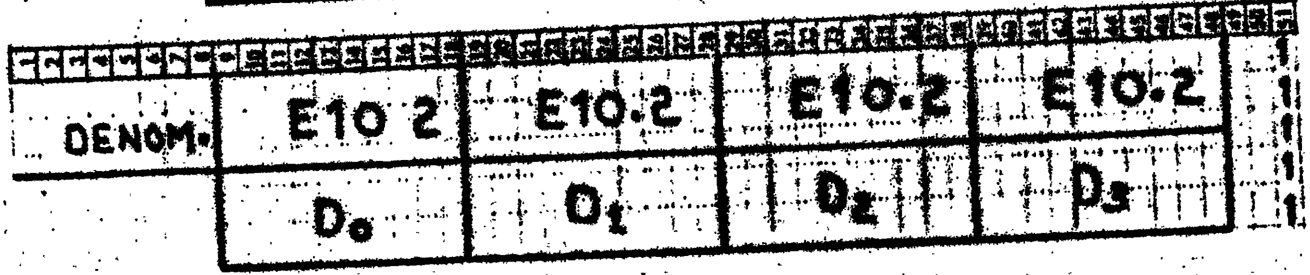
Next come TACS function blocks of Section 8.5.1 , plus the zero-th order blocks of Section 8.5.2 . The first card of each function block is interpreted as follows:



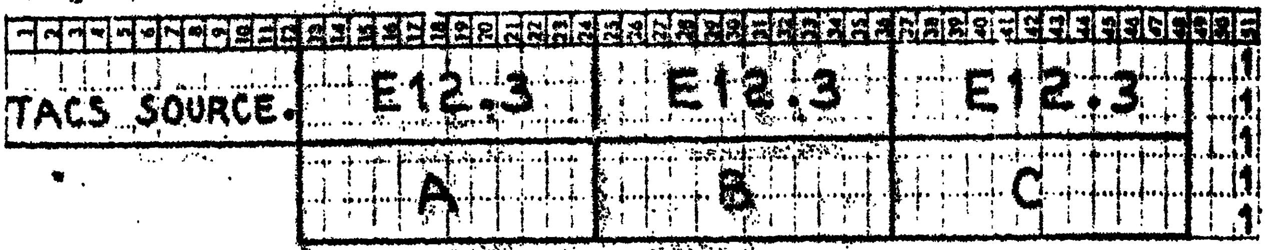
Here "N" is the order of the block, as read from columns 1-2 ; "output name" is the block name, as read from columns 3-8 ; and the block gain "GAIN" was read from columns 51-56.

For a dynamic block ($N > 1$), the polynomial coefficients of "s" of th transfer function follow, on two or more cards. The numerator coefficients precede the denominator coefficients. These two interpretations follow:





Next come TACS signal source cards of Section 8.5.4 . Interpretation is as follows, where "A" , "B" , and "C" are read from columns 11-40 using 3E10.0 format:

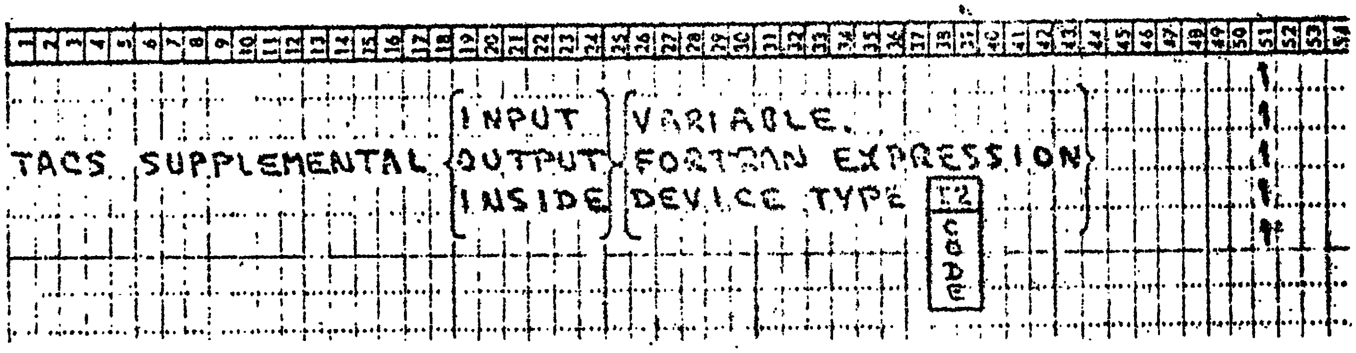


Next come TACS supplemental variables. Three types can now be defined:

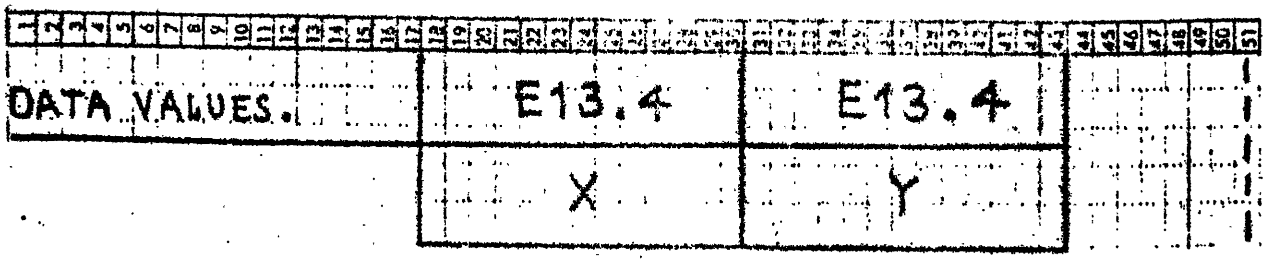
"VARIABLE" : old fixed-format expression
"FORTRAN EXPRESSION" : new free-format logical/algebraic FORTRAN expression
"DEVICE TYPE NN" : a TACS device type- 50, 51, 52, etc...

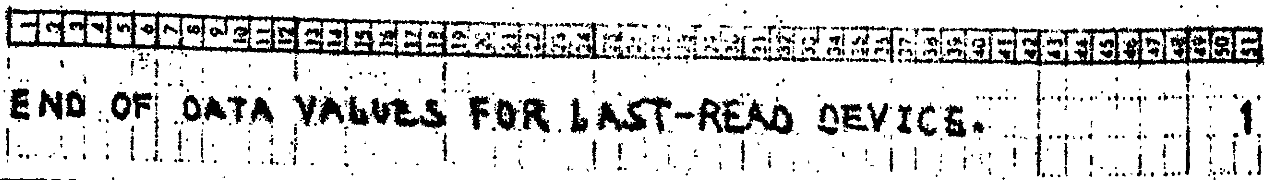
Each of the above may also belong to one of the three groups of supplemental variables: "inside", "input" and "output" .

The interpretation is then as follows:

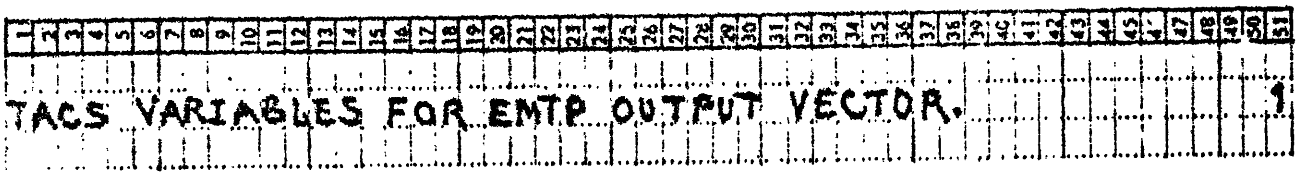


Certain TACS supplemental device cards may be immediately followed by an indeterminate number of associated data cards, each of which bears one or two floating-point numbers. Examples are the Type-55 digitizer, the Type-56 point-by-point nonlinearity, and the Type-57 time-sequenced switch. The end of such cards is marked by a "9999" card (punched in columns 13-16) . Interpretations are as follows:

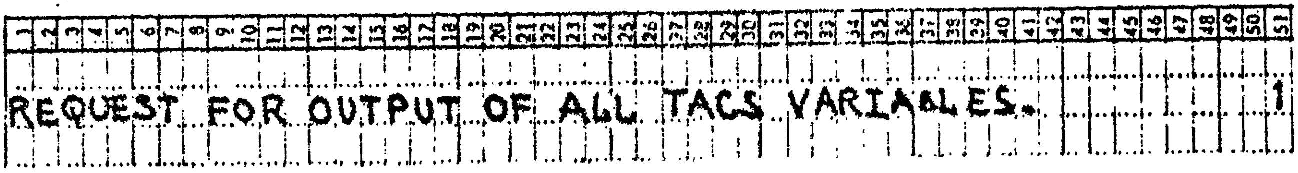




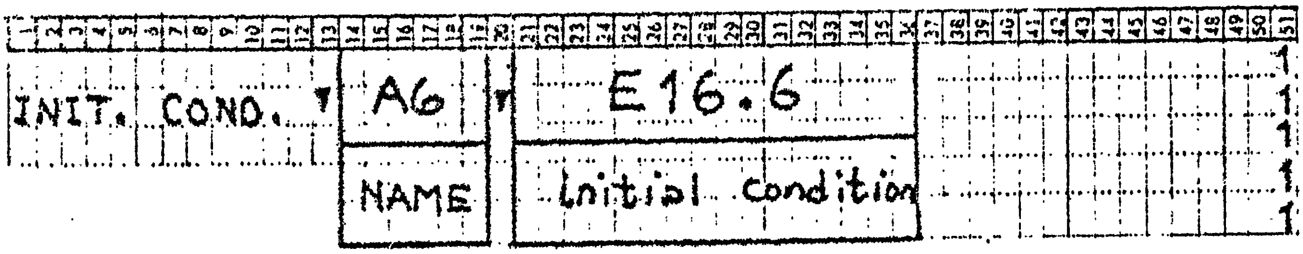
Next come the cards (or single card) which request TACS output variables, to be used for printing and/or plotting. For selectively-specified outputs, interpretation is:



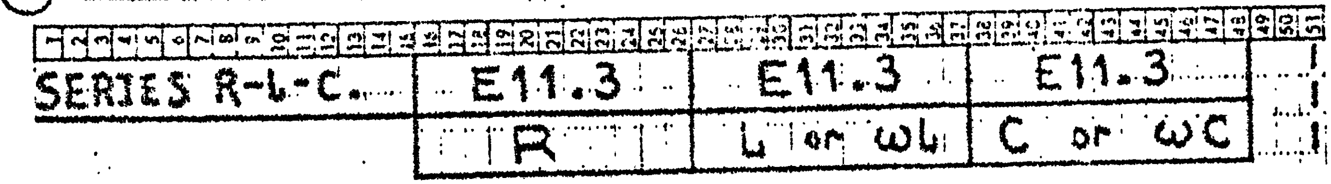
The output of all TACS variables can be requested by a single card with a "1"-punch in column 2. Interpretation is then as follows:



Finally come initial condition specification cards, if any. Interpretation is as follows:

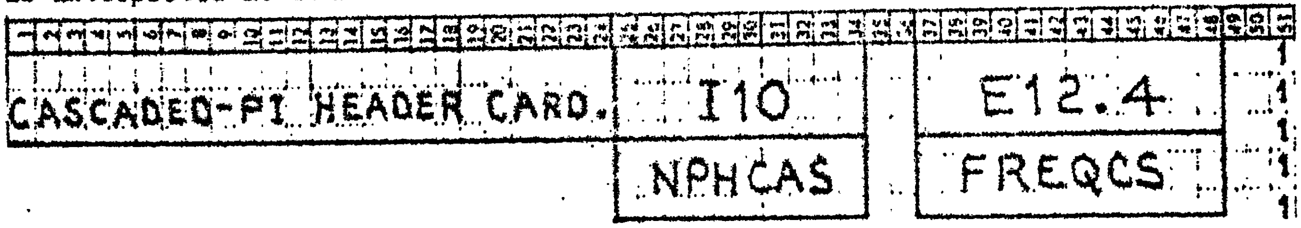


④ Lumped Series R,L,C (Section 1.21)



(4a) "CASCADED PI" Steady-State Component (Section 1.22)

Data input for a "branch" which is to be defined using the "CASCADED PI" feature of Section 1.22 begins with the header card (Class 1 input), which is interpreted as follows:



Class 2 data defines the terminal node names at the sending and the receiving ends, as well as matrices [R], [L], and [C] for the sending-end line section. Interpretation for these data cards is identical to that used for the conventional Pi-circuit component of Section 1.23. For convenience, this interpretation explanation is reproduced immediately below:

Here a distinction is made between the card for the first conductor of a Pi-equivalent and possible succeeding cards: The first card has the following interpretation:

1ST OF PI-CKT.	E11.3	E11.3	E11.3
	R_{11}	L_{11}	C_{11}

The first card of succeeding conductors of a multi-phase Pi-equivalent bear no descriptive text, with only the first 5 numbers of the card being printed out. Assuming conductor k,

E10.3	E10.3	E10.3	E10.3	E10.3
R_{k1}	L_{k1}	C_{k1}	R_{k2}	L_{k2}

The fourth and later conductors of course require continuation cards, since all parameters for row k can not be punched on a single card. For such cards, either 3 or 5 of the punched numbers are printed:

If the card has one triplet of numbers ($R_{k,m}$, $L_{k,m}$, $C_{k,m}$):

E10.3	E10.3	E10.3	E10.3	E10.3
R_{km}	L_{km}	C_{km}	R_{km}	L_{km}

If the card has two triplets, for columns m and m+1 ; or
If the card has 3 triplets, for columns m , m+1 , m+2 :

E10.3	E10.3	E10.3	E10.3	E10.3
R_{km}	L_{km}	C_{km}	$R_{k,m+1}$	$L_{k,m+1}$

Class 3 or Class 4 data is for the line-position (transposition) card, which is interpreted as follows:

LINE POS.	E11.3	I4	I4	I4	I4	I4	I4	I4
	DSECTJ	MULTIP	MSER	MBR	MSECT	MAPCAS1	MAPCAS2	MAPCAS3

Actually, if the line in question consists of more than 14 conductors, one or more "continuation" cards is needed for the input of MAPCAS(I) which was begun on the just-interpreted card. Each such extra card ("K" equal to 14 for the first; "K" equal to 28 for the second; etc.) would be interpreted as follows, if it existed:

I4	I4	I4	I4	I4	I4	I4	I4	I4	I4	I4	I4
$MAPCAS_{k+1}$	$MAPCAS_{k+2}$	$MAPCAS_{k+3}$	$MAPCAS_{k+4}$	$MAPCAS_{k+5}$	$MAPCAS_{k+6}$	$MAPCAS_{k+7}$	$MAPCAS_{k+8}$	$MAPCAS_{k+9}$	$MAPCAS_{k+10}$	$MAPCAS_{k+11}$	$MAPCAS_{k+12}$

Class 5 data is for the input of series R-L-C branches, each card of which bears the following interpretation:

SERIES R-L-C.	E11.3	E11.3	E11.3
	R_{series}	L_{series}	C_{series}

Class 6 data is for the input of shunt R-L-C branches, each card of which bears the following interpretation:

SHUNT.	I4	I4	E11.3	E11.3	E11 3
	N1	N2	R	L	C

Class 7 data is interpreted identically to Class 2 data.

Class 8 data consists of the single "STOP CASCADE" record, which is interpreted as follows:

TERMINATION OF CASCADED PI.	1

⑤ Pi-equivalent (Section 1.23)

Here a distinction is made between the card for the first conductor of a Pi-equivalent and possible succeeding cards. The first card has the following interpretation:

1ST OF PI-CKT.	E11.3	E11.3	E11.3	
	R_{11}	L_{11}	C_{11}	

The first card of succeeding conductors of a multi-phase Pi-equivalent bear no descriptive text, with only the first 5 numbers of the card being printed out. Assuming conductor k,

E10.3	E10.3	E10.3	E10.3	E10.3	1
R_{k1}	L_{k1}	C_{k1}	R_{k2}	L_{k2}	

The fourth and later conductors of course require continuation cards, since all parameters for row k can not be punched on a single card. For such cards, either 3 or 5 of the punched numbers are printed:

If the card has one triplet of numbers ($R_{k,m}$, $L_{k,m}$, $C_{k,m}$):

E10.3	E10.3	E10.3	E10.3	E10.3	1
R_{km}	L_{km}	C_{km}	R_{km}	L_{km}	

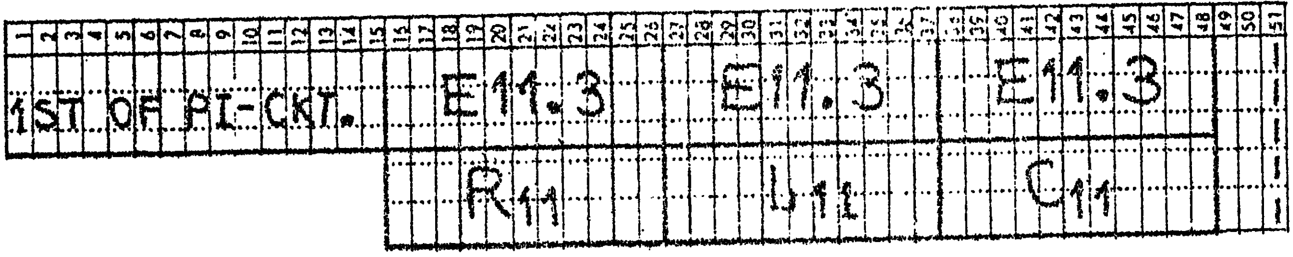
If the card has two triplets, for columns m and m+1 ; or
If the card has 3 triplets, for columns m , m+1 , m+2 :

E10.3	E10.3	E10.3	E10.3	E10.3	1
R_{km}	L_{km}	C_{km}	$R_{k,m+1}$	$L_{k,m+1}$	

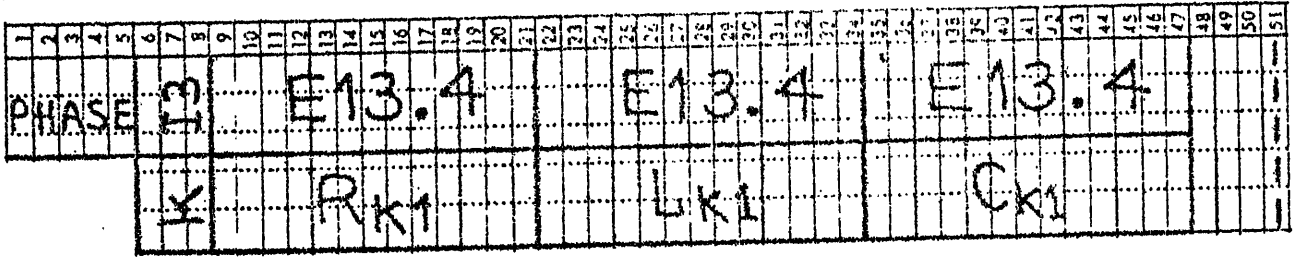
The user might rarely have occasion to employ the alternate formulation using matrices [A] and [B] in stead of the usual [R] and [L]. In this case, he will use the special formulation-change request records reading "USE AB" and "USE RL", which are interpreted as follows:

BEGIN COUPLED, LUMPED ELEMENTS USING (A), (B).	1
BEGIN COUPLED, LUMPED ELEMENTS USING (R), (L).	1

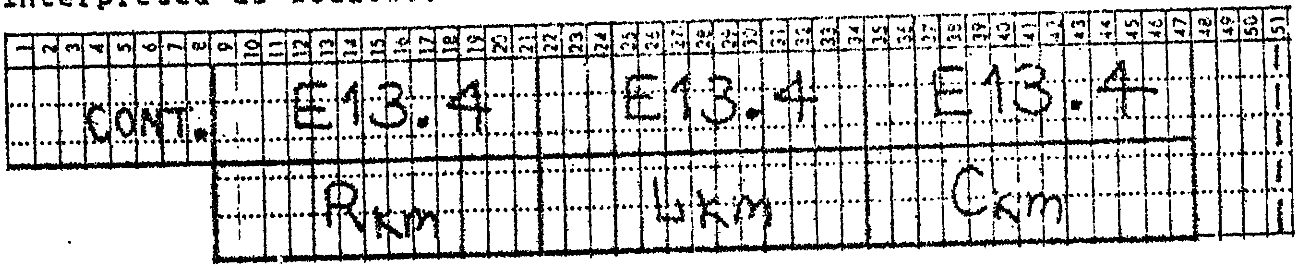
The preceding description assumes that the older, narrow formats are being used ($VINTAGE, 0). If instead the new, wider format is being used ($VINTAGE, 1), then any one data card only bears one triplet of numbers R(k,m), L(k,m), and C(k,m). The first data card is interpreted no differently than with the narrow formats (see top of section, "1ST OF PI-CKT."):



But the second and later cards (if any; if two or more phases) use a unique format. Interpretation of the data card which begins a new row K of the matrix (for K=2, 3, ...) is as follows:

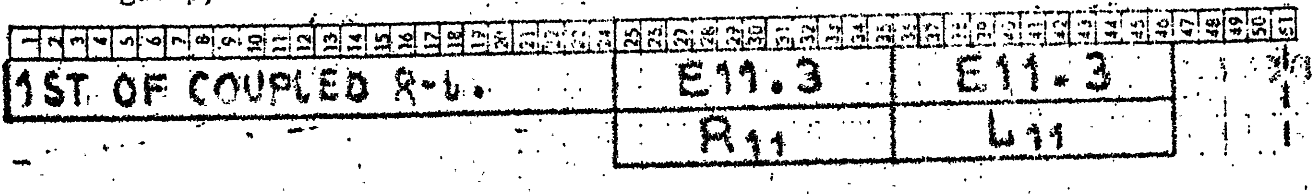


All other cards of the row (column M, for M=2, 3, ...) are interpreted as follows:



⑥ Coupled R-L Branches in Phase Values (Section 1.24)

A distinction is made between the card for the first conductor of a coupled R-L group, and all succeeding cards. For the first-conductor card:



All succeeding cards simply have printout of the 1, 2, or 3 pairs of R-L punched on the card, in order of increasing column number. For the extreme case having three pairs in row k , columns m through m+2 , the interpretation is:

E10.3	E10.3	E10.3	E10.3	E10.3
$R_{k,m}$	$L_{k,m}$	$R_{k,m+1}$	$L_{k,m+1}$	$R_{k,m+2}$

Should the user input zero and positive sequence values rather than the normal phase values, then interpretation of the 3 cards is as follows:

1. First card (with zero sequence values):

1ST OF COUPLED R-L.	E11.3	E11.3
	R_0	L_0

2. Second card (with positive-sequence values):

E10.3	E10.3	E10.3	E10.3	E10.3
R_1	L_1	0.0	0.0	0.0

3. The third card gives the third row of the matrices as if the input had been made in phase quantities; it gives the phase equivalent of the preceding sequence values:

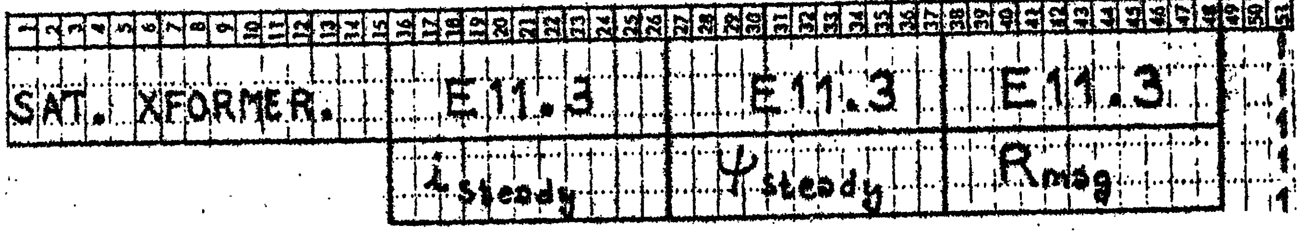
E10.3	E10.3	E10.3	E10.3	E10.3
R_m	L_m	R_m	L_m	R_s

Just as with Pi-circuits of Section 1.23, it is possible to employ the alternate formulation using matrices [A] and [B] instead of the usual [R] and [L]. In this case, the user inputs special request records reading "USE AB" and "USE RL" , which are interpreted as follows:

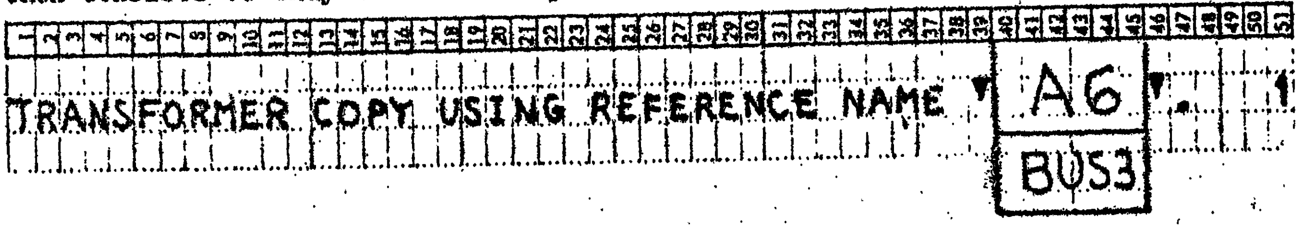
BEGIN COUPLED, LUMPED ELEMENTS USING (A), (B).	1
BEGIN COUPLED, LUMPED ELEMENTS USING (R), (L).	1

⑦ Saturable Transformer Component (Section 1.25)

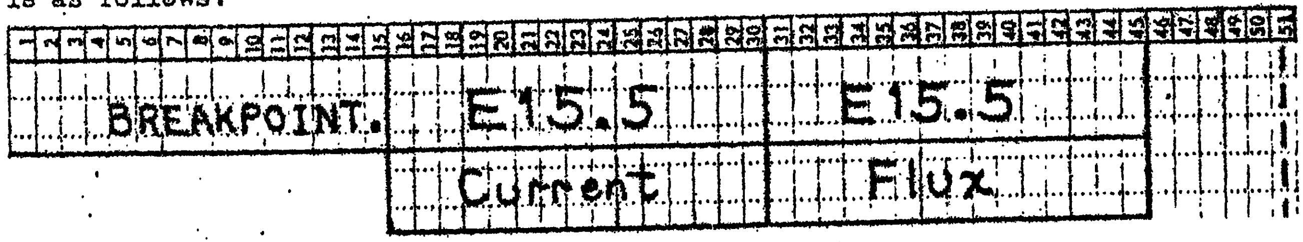
The first card of a single-phase saturable transformer component bears the special request word "TRANSFORMER" , which is interpreted as follows:



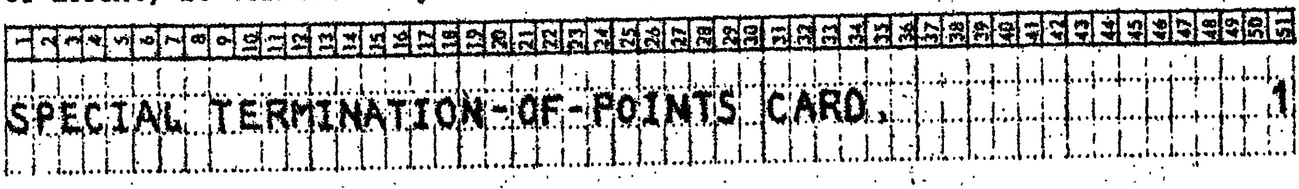
Actually, this interpretation assumes that the reference component feature has not been used to define this unit (i.e., field "BUS3" of cols. 15-20 are blank). If the reference component feature is being used, interpretation then consists of only the following:



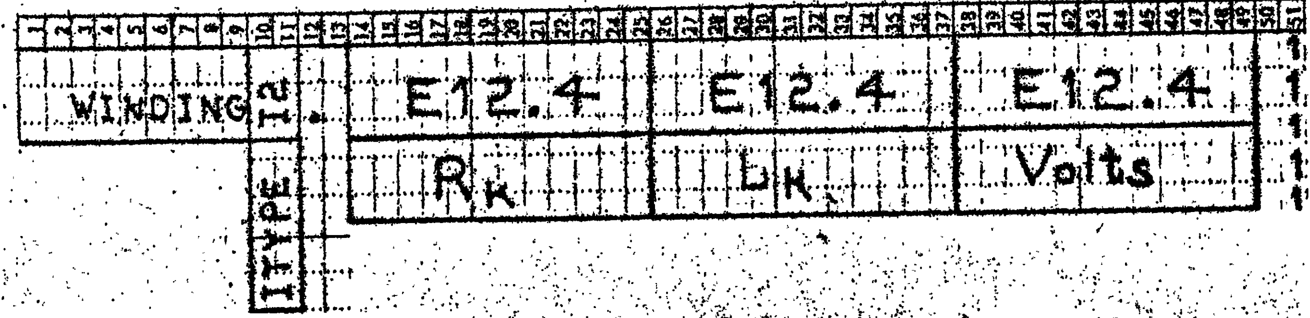
Assuming no use of the reference component feature, the "TRANSFORMER" request card is followed by current-flux breakpoints (if any) which define the magnetization characteristic. Interpretation of all such records, if any, is as follows:



With no reference component usage, the preceding data class (whether present or absent) is terminated by a 9999-card, which is interpreted as follows:



Next come the transformer winding cards, which are interpreted as follows assuming no usage of the reference-component capability:



If reference component usage were being employed for this unit, columns 14-49 of the above interpretation for a winding card would have been left blank. This is because the winding card in question bears no floating-point parameters in such a case.

Finally, if a 3-phase, 3-leg core-type transformer component is desired by the user, the three single-phase units for each phase are all preceded by the special 3-phase request card reading "TRANSFORMER THREE PHASE" (cols. 3-25 key-word text). Interpretation of such a card is as follows:

3-PHASE XFORMER REQUEST.	A6	E12.4	1
	BUS3PH	R_0	1

⑧ Distributed-Parameter Transmission Line, Continuously-Transposed (Sect. 1.26)

The first two cards of a distributed-parameter line, carry the zero and positive-sequence parameters respectively. Interpretation consists of 3 principal floating-point values read from the card, plus the characteristic impedance Z_0 (computed neglecting line loss) and the travel time τ:

E10.3	E10.3	E10.3	E10.3	E10.3	1
R	A	B	$Z_0 = \sqrt{L/C}$	$\tau = \ell\sqrt{LC}$	1

If the line is continuously transposed (Section 1.26), then the third and any later cards only define the terminal node names, and are therefore only interpreted by the message:

3RD OR LATER UNIF.-TRANSPOSED DISTRIBUTED COND.	1

But if instead the component is a double-circuit distributed-parameter line with zero-sequence inter-circuit coupling (Section 1.26a), then interpretation of the third card is identical to the first two; in this case, the 3rd card has parameters for the "IL" mode. The fourth through sixth conductor cards then bear the following interpretation:

4TH OR LATER DOUBLE CKT DISTRIBUTED CONDUCTOR.	1

Should the first card (zero-sequenc parameters) of a distributed-parameter transmission line carry a request for frequency-dependent representation (a "-1" punched in columns 53-54, field IPUNCH), the added data outlined in Section 1 26b must follow.

First, the miscellaneous data card bears the following interpretation:

1–51
FREQUENCY-DEPENDENCE MISC. DATA VALUES.

Then each card defining one or more points of the far-end (forward) weighting function $a_1(t)$ bears the identification

1–51
WEIGHTING FUNCTION A1 POINTS.

Finally, each card defining one or more points of the near-end (backward) weighting function $a_2(t)$ is interpreted as:

1–37	38–49	50–51
WEIGHTING FUNCTION A2 POINTS.	F12.8	
	Area	

Here the field AREA (cols. 38-49) only applies to the last card defining $a_2(t)$, where the total area under the weighting functions, $\text{AREA} = \int_0^\infty a_1(t)dt + \int_0^\infty a_2(t)dt$ is printed out. For valid weighting functions, this should be near unity (like 1.005).

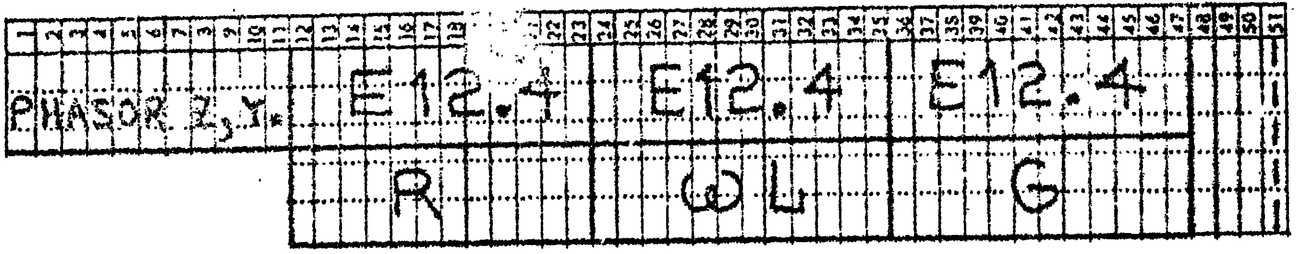
An exception to this complete display occurs if variable LIST (columns 57-64 of the frequency-dependence miscellaneous data card) is punched equal to unity rather than zero. Then none of the A1(t) data cards is displayed or interpreted, and only the final two A2(t) cards are shown. The interpretation of these final two data cards is exactly as they would appear if LIST were zero.

⑨ Recursive Convolution Frequency Dependence (Section 1.27)

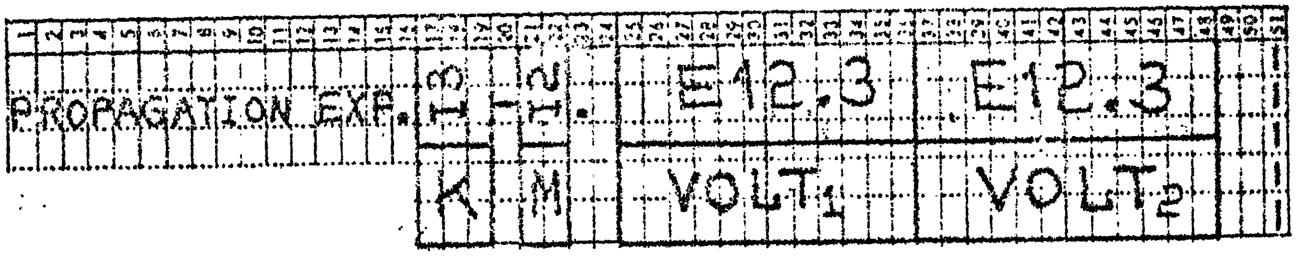
A frequency-dependent untransposed transmission line uses data cards as documented in Section 1.27 . Typically these will be generated by the EMTP itself, using either the "SEMLYEN SETUP" feature of Section 7.5 , or the "HAUER SETUP" feature of Section 7.8 . Interpretation begins with the branch card of Rule 1 ; for phase (mode) K,. one has:

1–12	13–25	26–38	39–42	43–46	47–51
CONVOLUTION.	E13.4	E13.4	I4	I4	
	γ_0	τ	N1	N2	

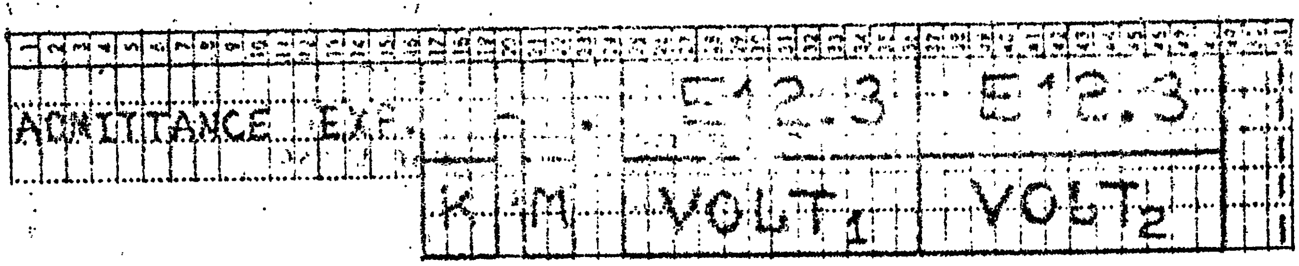
Immediately after such a branch (mode) card comes the steady-state card of modal impedances, to be used during the phasor solution for initial conditions. Interpretation is as follows:



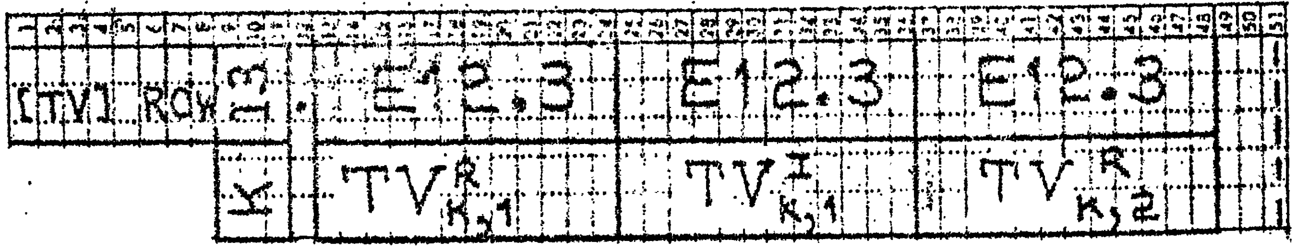
Next comes an indeterminate number of data cards which characterize the modal wave propagation. The exponentials are numbered 1, 2, 3, etc., with any one data card typically bearing two consecutive ones of these. That is, card one bears the first two exponentials, card two bears exponentials 3 and 4, etc. Interpretation for the data card bearing exponentials K through M is as follows:



After the last data card of propagation exponentials for the mode, we have one or more such cards for the admittance exponentials. Just as with the propagation exponentials, there are typically two per card. Interpretation is comparable, too:

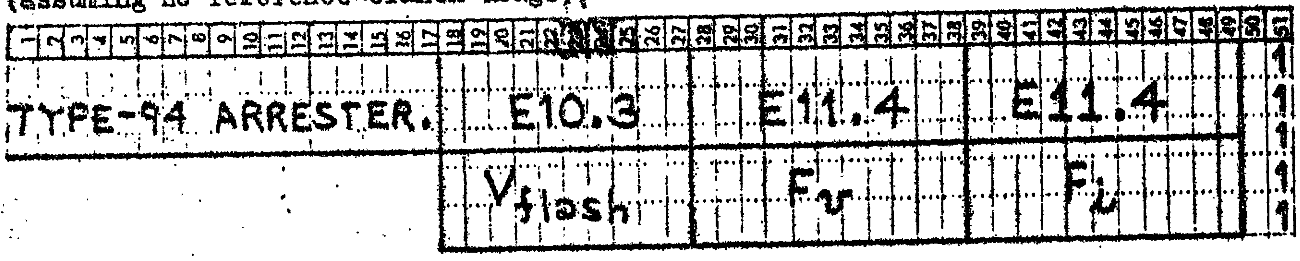


So much for the two components of Rule 3 data. Such data (Rules 1, 2, and 3) are cyclically repeated for each branch (mode) of the multi-phase transmission circuit (see Rule 4). After the last such mode, we have data cards which specify the voltage transformation matrix [Tv] of Rule 5. This is inputted by rows, from left to right within a row, with 3 matrix elements on any one data card. For one of the data cards of row K of the matrix, interpretation is as follows:

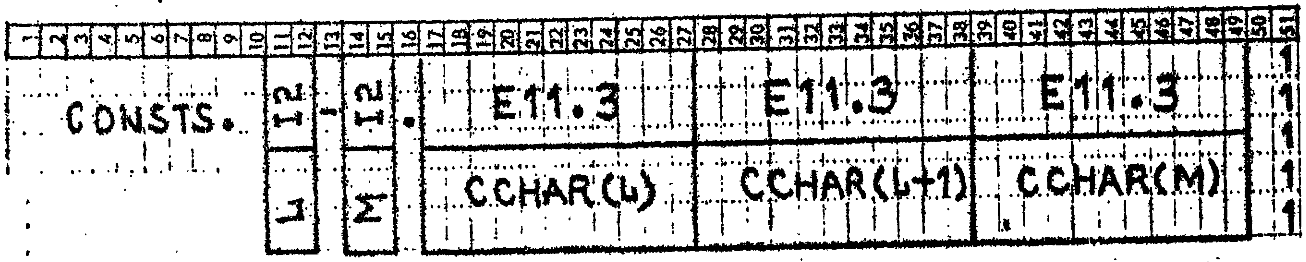


(10a) Type-94 Surge Arrester

Section 1.38 describes the various data cards which are associated with the Type-94 modern-style silicon-carbide surge arrester component (with current limiting gap). These begin with a branch card, which is interpreted as follows (assuming no reference-branch usage):



Then come six cards bearing floating-point parameters of the arrester —— three numbers on each of the first five cards, and two on the final one. These cards are interpreted in the following way:



Here "L" and "M" are beginning and ending indices for the FORTRAN EMTP storage of the constants on the card. For the six cards, these indices should read as follows:

Card #	1	2	3	4	5	6
L	1	5	8	11	14	17
M	3	7	10	13	16	18

If the reference-branch procedure were used (fields "BUS3" and "BUS4" of columns 15-26 not both blank), then only one card would be involved, and this would be interpreted as per Point 11 .

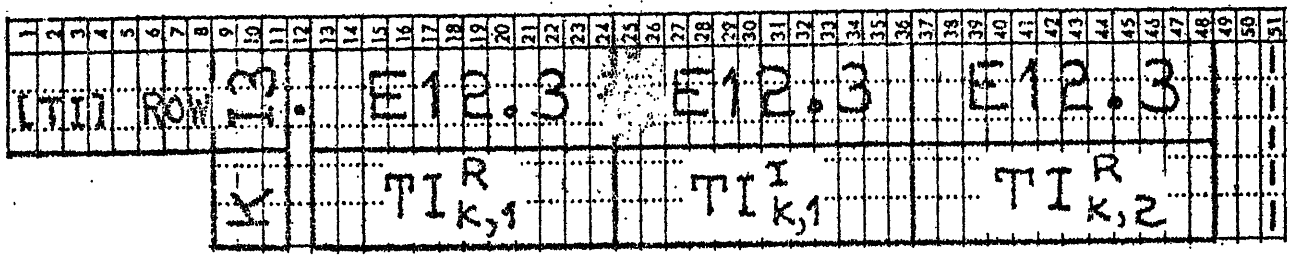
(10b) Multi-phase ZnO surge arresters

Section 1.32 describes the various data cards which are associated with multi-phase, compensation-based, ZnO surge arrester modeling. These begin with the definition of Type-92 nonlinear elements which have dummy characteristics. Because interpretation of such data cards is covered elsewhere, it shall not be repeated here.

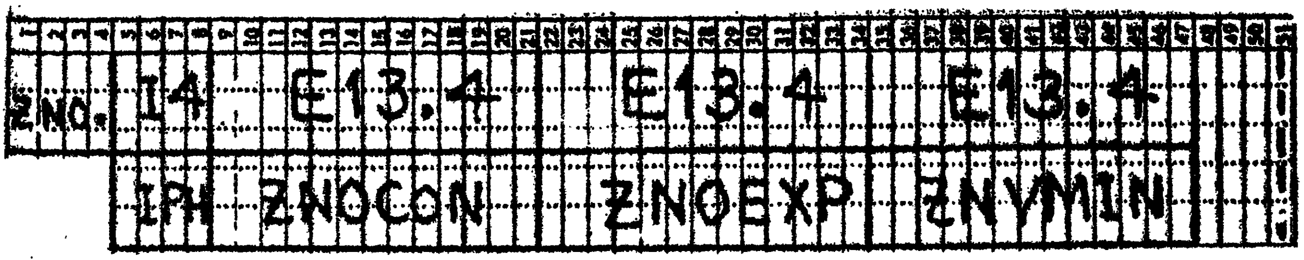
But all new are the data cards which precede the specification of network node voltage outputs. This is where the actual characteristic and associated iteration constants are provided by the user.

First, there is the single-exponential case, with no gap, as requested by phase number IPHASE = IPH bearing a minus sign. Then only one data card is required for each arrester, and it is interpreted as follows:

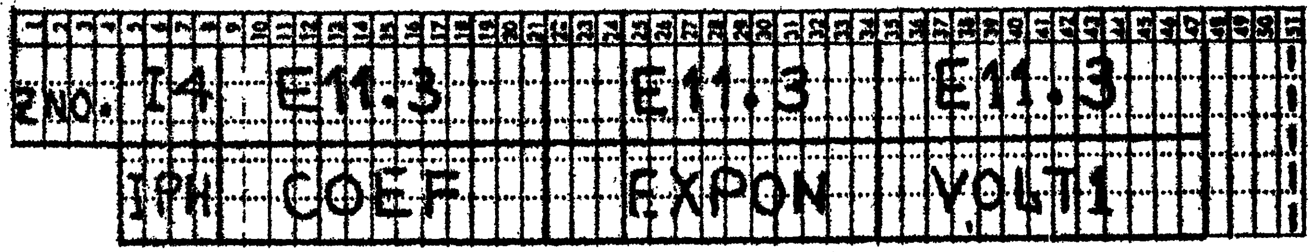
Finally, we have the current transformation matrix [Ti] , as described in Rule 6 . Format is the same as for [Tv] . For one of the cards of row K , data card interpretation is:



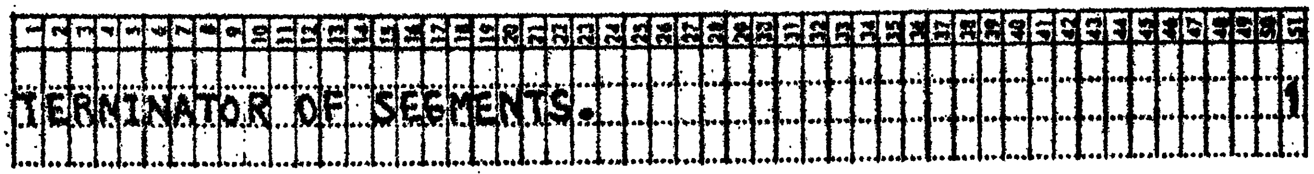
It should be mentioned that a corresponding input for the branch cards of "AMETANI SETUP" (see Section 7.6) also exists, though as of the summer of 1980 it has not been debugged. Bob Eifrig coded the exponential (Semlyen) and piecewise-linear (Ametani) recursive convolution codes together during the summer of 1978. This was the new code, with an indeterminate number of exponentials, and an indeterminate number of linear segments. But we were pressed for time, and simply could not pursue both. In cooperation with Ontario Hydro, we chose to pursue the exponential (Semlyen) modeling. The Ametani modeling remains untested, so is not recommended for the general public. Indeed, because Bob Eifrig had to alter data formats as part of the generalization, the data cards punched by "AMETANI SETUP" no longer are accepted by the new code. More work is needed, then. Any volunteers?



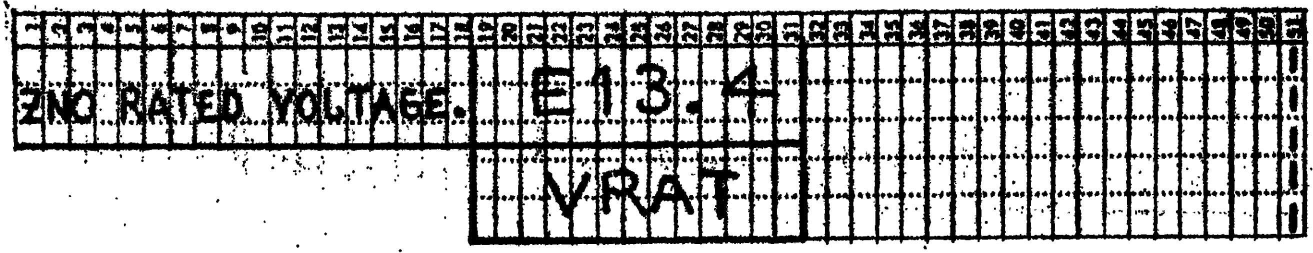
On the other hand, if the multi-exponential model with a gap is chosen, as indicated by a positive phase number IPHASE = IPH , then several data cards are required for each arrester. The data cards for each segment of the characteristic are interpreted similarly to those for the single-exponential case:



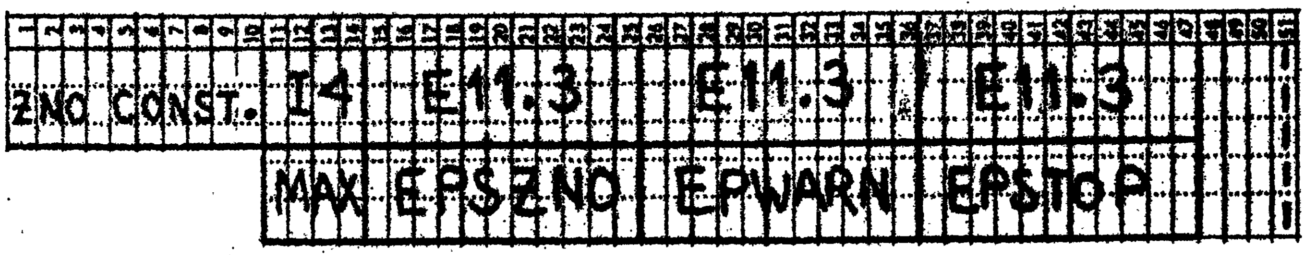
Recall that there is an indeterminate number of these (temporarily fixed in number at two, as of August, 1980), terminated by a 9999-card. This termination card bears the interpretation:



The characteristic before flashover appears first, followed by the characteristic after flashover. When both are complete (after the second 9999-card), there follows the card bearing rated voltage. Interpretation is as follows:



So much for the data cards which apply to individual ZnO surge arresters. After the last of these, there is a single data card which controls the Newton iteration. Interpretation is as follows:

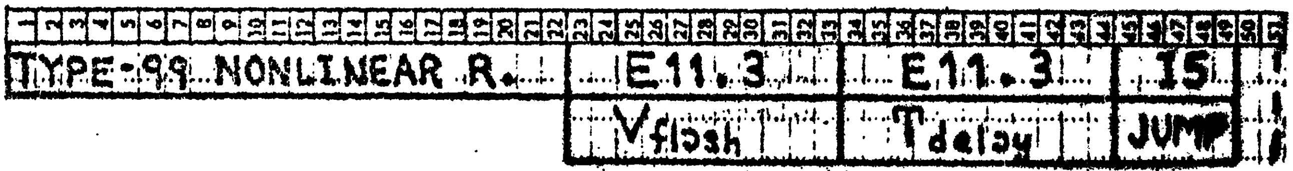


10C Branch Element Types 91-93 and 96-99.

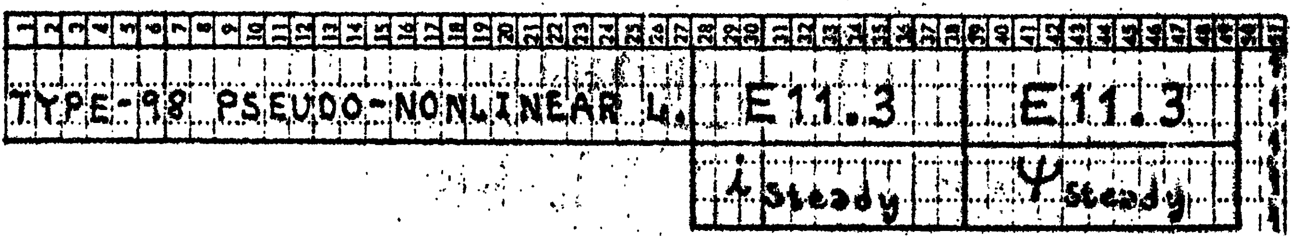
For purposes of documenting the interpretation, it is convenient to lump together all remaining nonlinear and pseudo-nonlinear elements. These have type codes 91, 92, 93, 96, 97, 98, and 99, as described in Sections 1.28 onward.

Definition of each of these elements begins with a first data card which specifies the terminal node names, among other things. Assuming no usage of the reference branch procedure, interpretations are as follows:

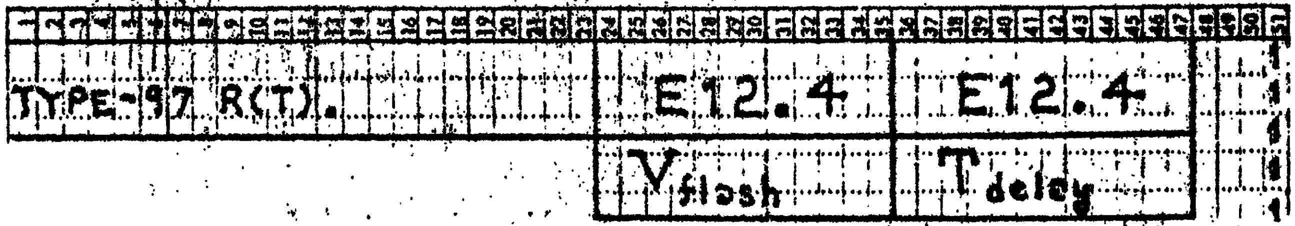
1. Pseudo-nonlinear R, type 99 (Section 1.28)



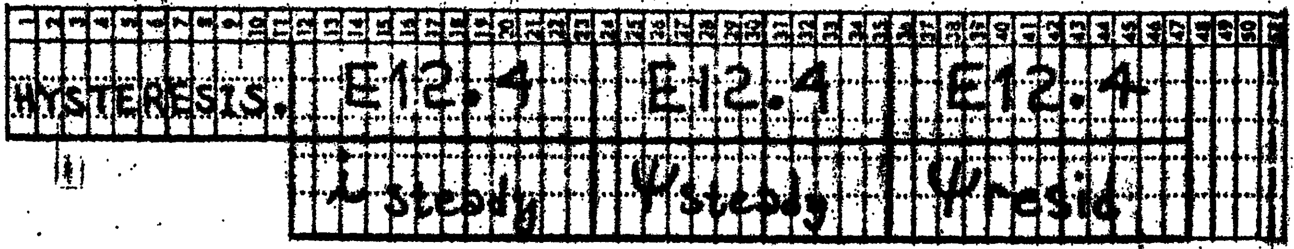
2. Pseudo-nonlinear L, type 98 (Section 1.29)



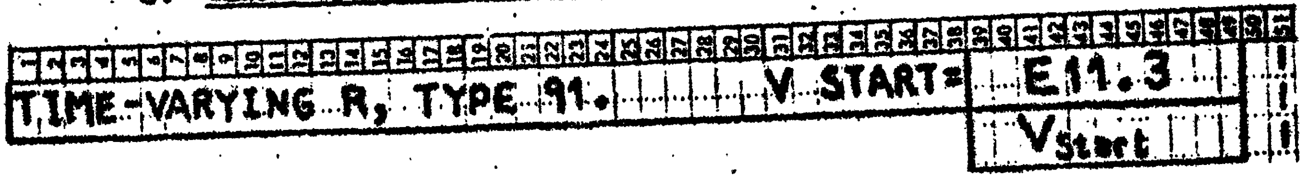
3. Staircase time-varying R, type 97 (Section 1.30)



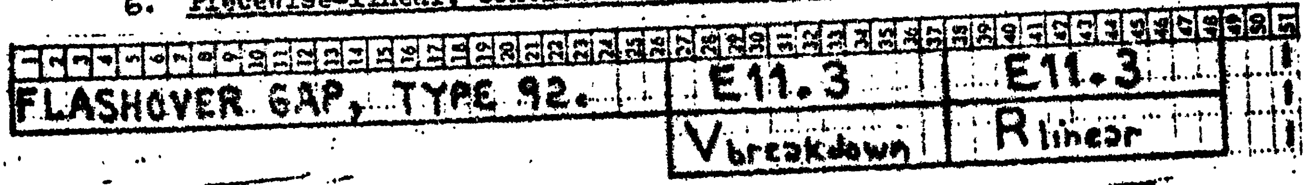
4. Pseudo-nonlinear hysteretic reactor, Type 96 (Section 1.31)



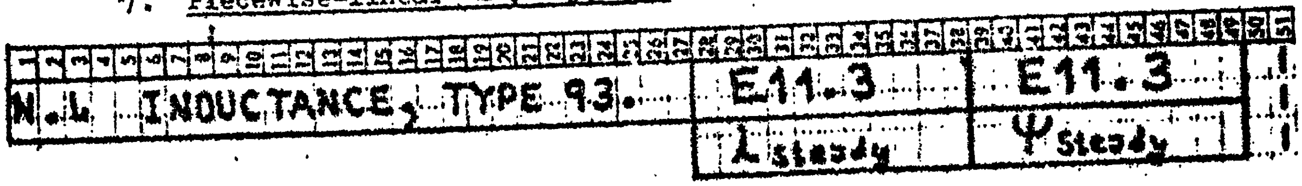
5. Time-varying R , type 91 (Section 1.35)



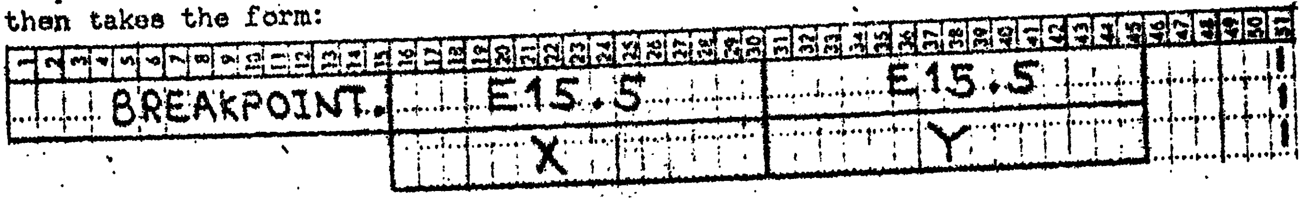
6. Piecewise-linear, continuous R , type 92 (Section 1.36)



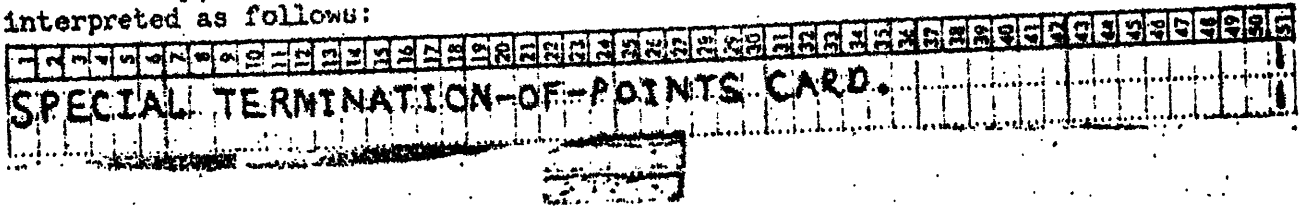
7. Piecewise-linear L , type 93 (Section 1.37)



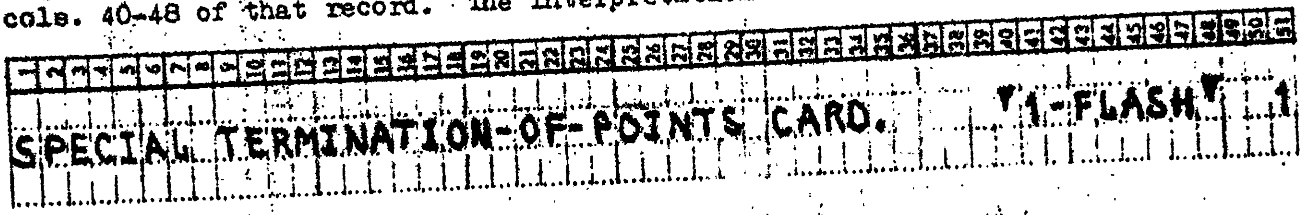
Following this lead card are the cards defining the breakpoints of the piecewise-linear curve in question. Using X and Y to symbolize the pairs of points that are being inputted, the interpretation for all element types then takes the form:



Finally, the preceding breakpoints are terminated by the 9999-card, interpreted as follows:



In case the "SINGLE FLASH" option for a type-99 element is being requested on the 9999-card, then added interpretation is provided in cols. 40-48 of that record. The interpretation for such a special case is:



⑪ Branches using the Reference-Branch Idea

When the reference-branch concept is used, fields BUS3 and BUS4 (columns 15-26 of data card) carry the node names of the preceding branch which is being referred to. The first card of a coupled group using this capability bears the following interpretation:

1-18	19-26	27-32	33-38	39-44	45-51
REFERENCE BRANCH.	COPY '	A6	' TO '	A6	'
		BUS3		BUS4	

All later branches of the coupled group (if any) bear the following abbreviated interpretation

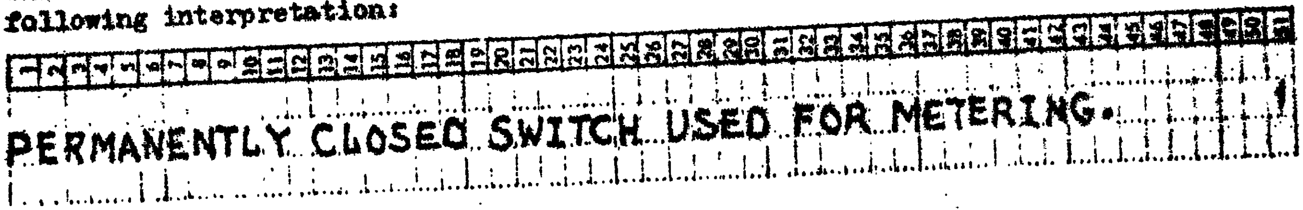
1-18	19-51
REFERENCE BRANCH.	COPY CONT.

⑫ Switches and Switched Elements (Section 1.4)

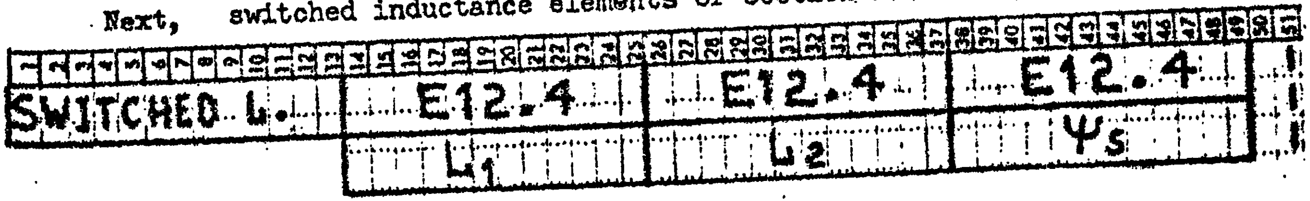
The "ordinary" switches of Section 1.40 are EMTP switch components which have no linear resistance or inductance element associated with them, and which are not valves, diodes, or TACS-controlled. Generally these switches are of type-code zero (as punched in columns 1-2), although type-code '76' is also possible for a Class 3a switch. Ordinary switches come in five classes, with the first four interpreted as per the following format:

1-8	9-18	19-28	29-38	39-48	49-51
SWITCH.	E10.2	E10.2	E10.2	E10.2	
Class 1	T_{close}	T_{open}	I_{ϵ}	▭	
Class 2	T_{close}	T_{delay}	I_{ϵ}	V_{flash}	
Class 3a	$\overline{T}$ or $\overline{T}_{B}$	σ or σ_{B}	▭	▭	
Class 3b independent	T_{mid} or T_{beg}	ΔT	NSTEP	▭	
Class 3b dependent	T^{B}_{offset}	▭	▭	▭	

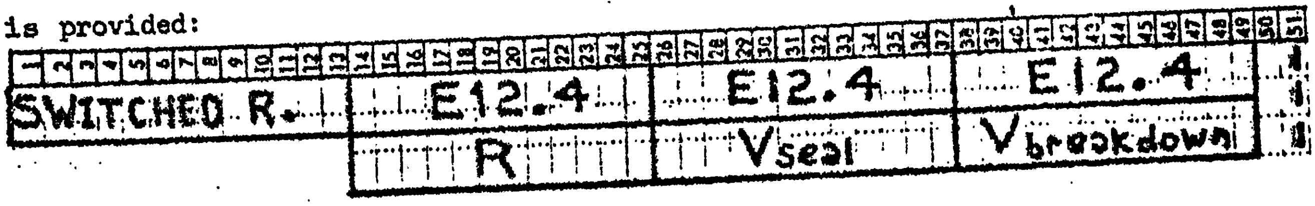
The final one, for Class 4 switches ("MEASURING" switches), bears the following interpretation:



Next, switched inductance elements of Section 1.41 carry the interpretation:



For switched resistance elements of Section 1.42, the following interpretation is provided:



For diode or TACS-controlled valve operation, the type-11 switch of Section 1.43 is used.

Parameter "GRID" is read from the A6 field in columns 65 - 70 .
Parameter "CLAMP" is read from the A6 field in columns 71 - 76 .

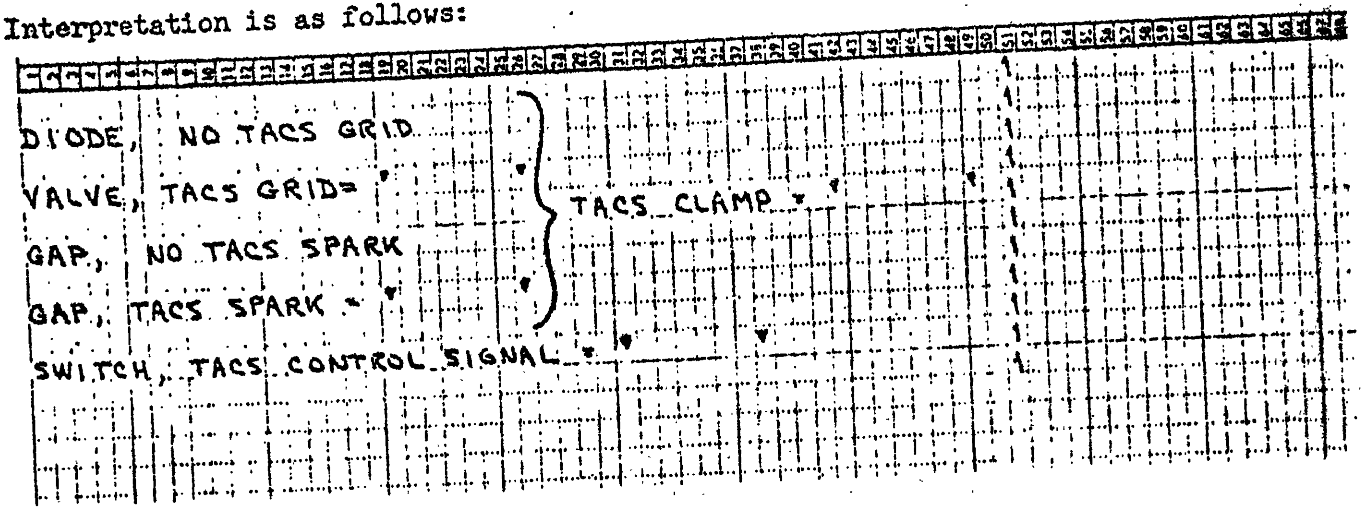
For diode or TACS-controlled valve operation, the type-12 switch of Section 1.44 is used.

Parameter "SPARK" is read from the A6 field in columns 65 - 70 .
Parameter "CLAMP" is read from the A6 field in columns 71 - 76 .

For simple TACS-controlled switch operation, the type-13 switch of Section 1.45 is used.

Parameter "SIGNAL" is read from the A6 field in columns 71 - 76 .

Interpretation is as follows:



(13) Sources (Section 1.6)

Source cards are interpretated as follows, for sources Type 1-15 :

SOURCE	E10.2	E10.2	E10.2	E10.2	1
	AMPL	f ; α	T_0 ; ϕ_0 ; β	T_{start}	1

For type-16 DC-simulator sources, the first card is interpreted as:

SOURCE.	E10.2	E10.2	E10.2	E10.2	1
	K	δ_{init} ; λ_{set}	T_1	$\lambda_{initial}$	1

The second and final card then bears only the label:

SECOND DC SIMULATOR CARD.	1

The Type-17 EMTP source component provides for representation of a zinc-oxide surge arrester that has constraint equation $i = A * (v/v_{ref})^G$. Interpretation is as follows:

SOURCE.	E10.2	E10.2	E10.2	E10.2	1
	A	G	v_{ref}		1

Type 1-10 sources have the functions $f(t)$ read in off cards in point-by-point fashion, as the transient solution progresses. Assuming that the user is printing out solution results, the input card images may be periodically separated by such printed output. In any case, the interpretation of the source cards of type 1-10 is as follows:

ANOTHER INPUT CARD FOR TYPE 1-10 SOURCES.	1

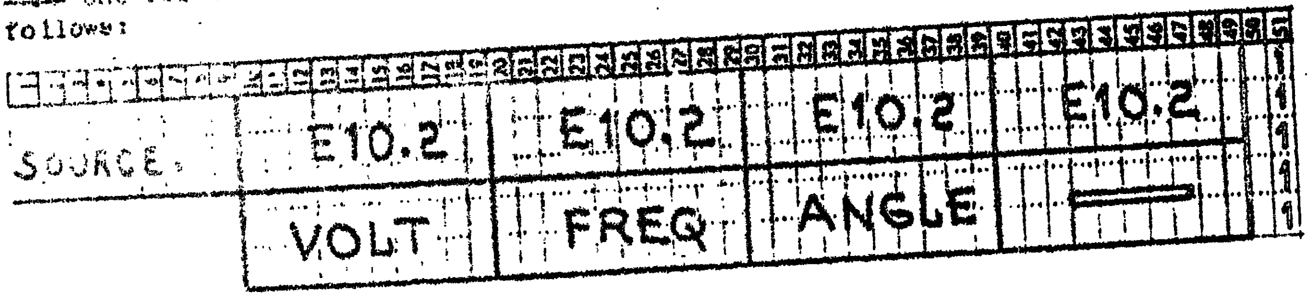
If all such source definitions are to terminate before the last time step of the EMTP simulation, then a bounding record with "9999" punched in columns 5-8 is to be used. This last card then bears the added column 45-48 interpretation as shown at the right.

END.	1

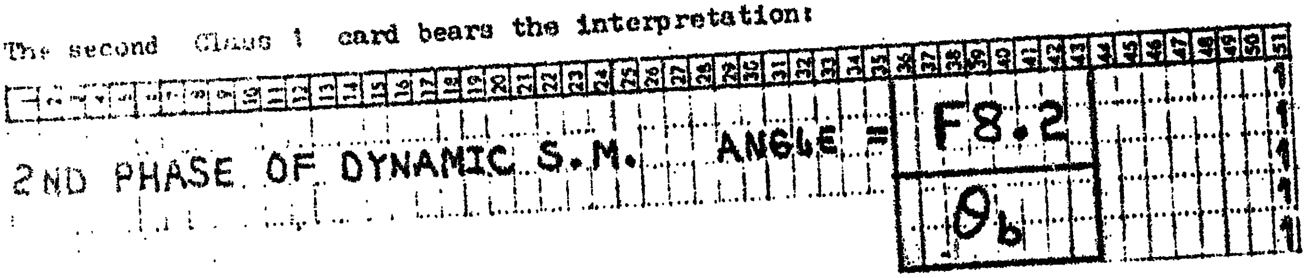
(13a) Dynamic Synchronous Machines (Section 1.62)

Data input for dynamic synchronous machine (S.M.) EMTP source components is described in Section 1.62 . The type-code which i punched in columns 1-2 will be equal to 50 or more, in this case. Each dynamic S.M. requires a number of data cards, the interpretation of which shall now be described in order of data input.

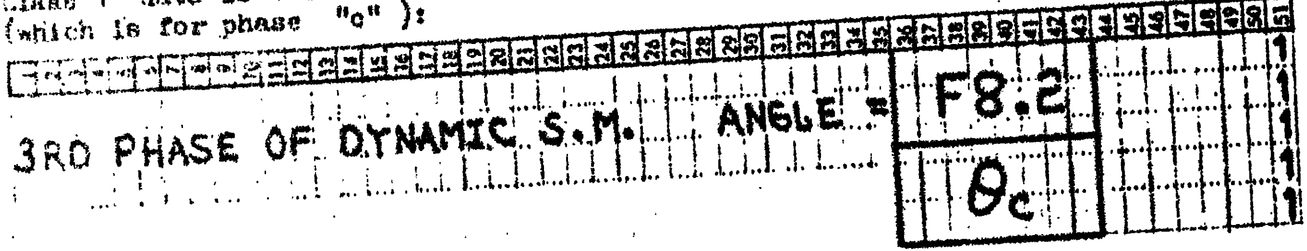
The S.M. cards begin with Class 1 data, for which there are three cards —— one for each armature connection. The first of these is interpreted as follows:



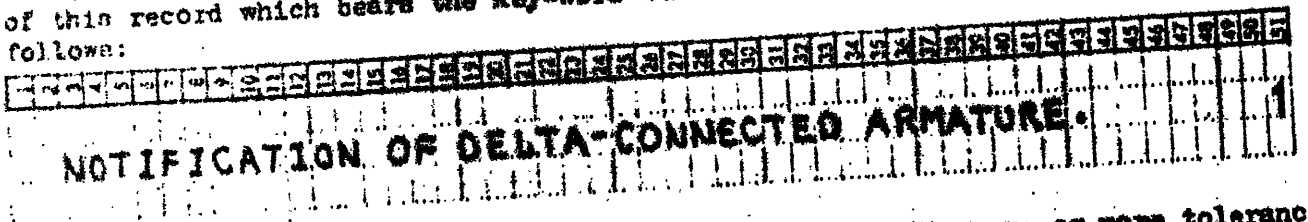
The second Class 1 card bears the interpretation:



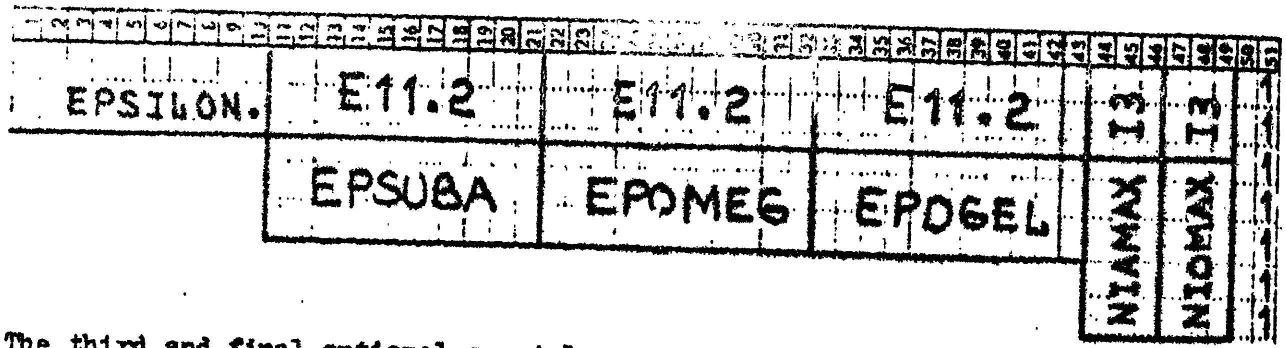
Here the printed angle is in degrees. Rather than representing data which is read from the card, this angle of phase "b" is internally calculated; it is equal to "ANGLE" as read from the first card, decreased by 120 degrees. Class 1 data is then finished by a comparable interpretation for the third card (which is for phase "c"):



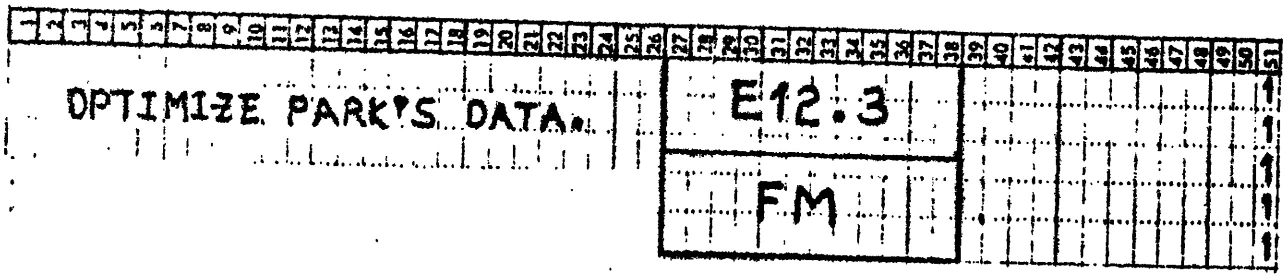
Class 2 S.M. data (if it exists) consists of up to three optional special-request cards, of which the order is immaterial. One of these represents a request for a delta connection of the S.M. armature windings. Interpretation of this record which bears the key-word text "DELTA CONNECTION" is as follows:



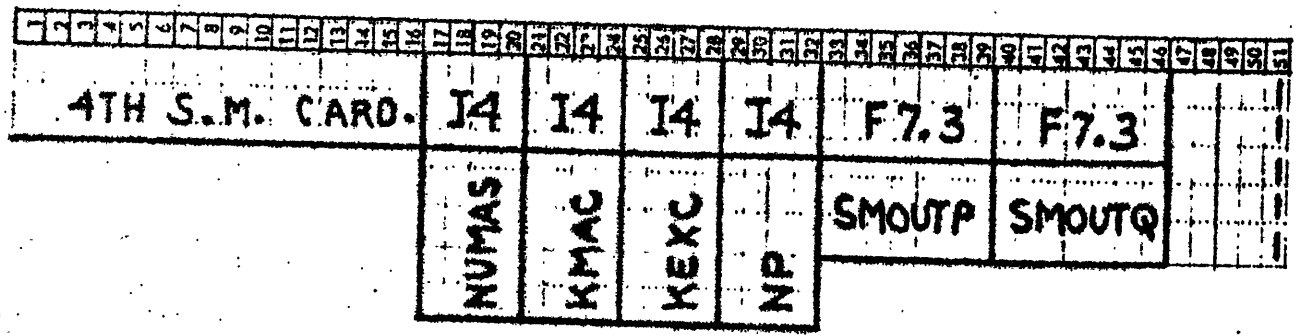
The second optional special-request card is used to redefine one or more tolerances or iteration limits which are used in the S M. solution proc ss. Interpretation of this record which bears the key-word text "TOLERANCES" is as follows:



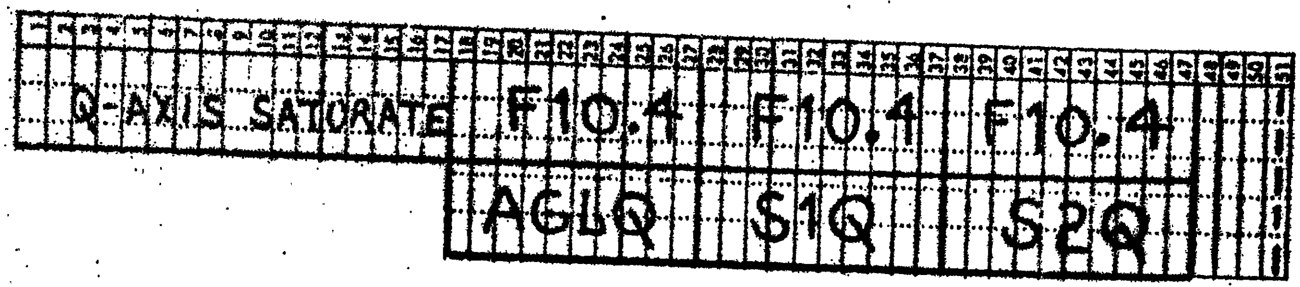
The third and final optional special-request card is used to obtain the mathematical fitting of the S.M. parameters of Park's equations to the available data. Interpretation of this record which bears the key word "PARAMETER FITTING is as follows:



Class 3 S.M. data consists of either 3 or 4 cards, the first of which bears the following interpretation:



The saturation data on this card applies to the direct axis. But there also is the question of possible quadrature-axis saturation, addressed by the following optional card whose presence is recognized by blank columns 1-48 of the card immediately following "4TH S.M. CARD." . If present, it will be interpreted as follows:



The remaining cards of Class 3 S.M. data depend upon whether standard manufacturer-supplied data are being used. If so (if the machine has type code 50 or 51), then two additional cards which are interpreted as follows complete the Class 2 data:

5TH S.M. CARD.	F10.4	F10.4	F10.4	
	R_a	X_ℓ	X_d	

6TH S.M. CARD.	F10.4	F10.4	F10.4	
	T'_{do}	T'_{qo}	T''_{do}	

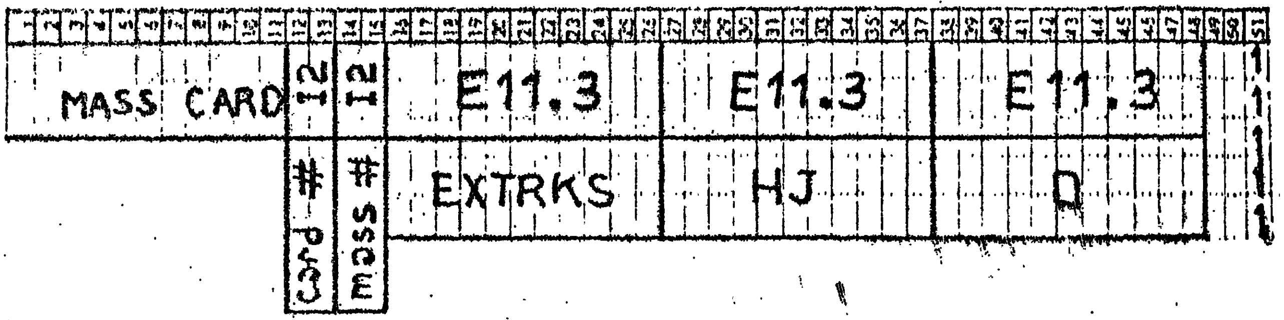
On the other hand, should the user have chosen to describe the machine by means of per unit inductance and resistance matrices (type codes 52 or 53), then the Class 2 S.M. data is completed with three cards which are interpreted as follows:

5TH S.M. CARD.	F10.4	F10.4	F10.4	
	L_f	L_{af}	L_{fkd}	

6TH S.M. CARD.	F10.4	F10.4	F10.4	
	L_q	L_{aq}	L_{qkq}	

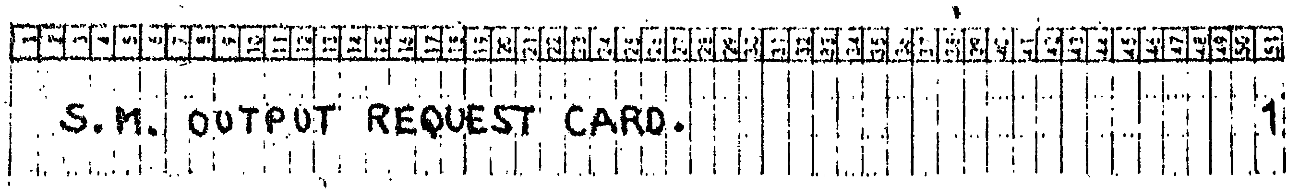
7TH S.M CARD.	F10.4	F10.4	F10.4	
	X_0	R_a	R_f	

Class 4 S.M. data consists of mass cards, one for each mass of the shaft system of the rotor. Interpretation of each such card is as follows:

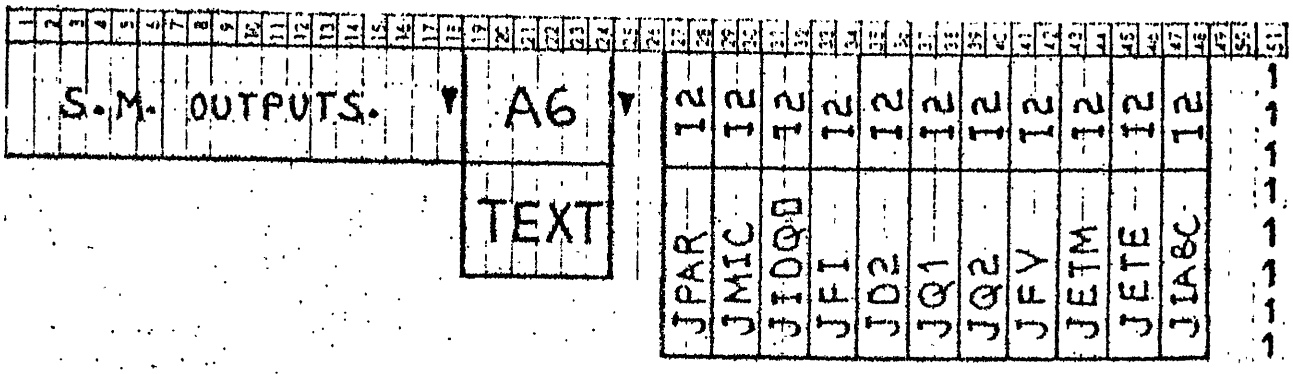


Here the "MASS #" is the number of the mass (variable "ML") as read from columns 1-2 of the card. The "CARD #" is simply a counter which is equal to unity for the first such mass card, equal to two for the second, etc.

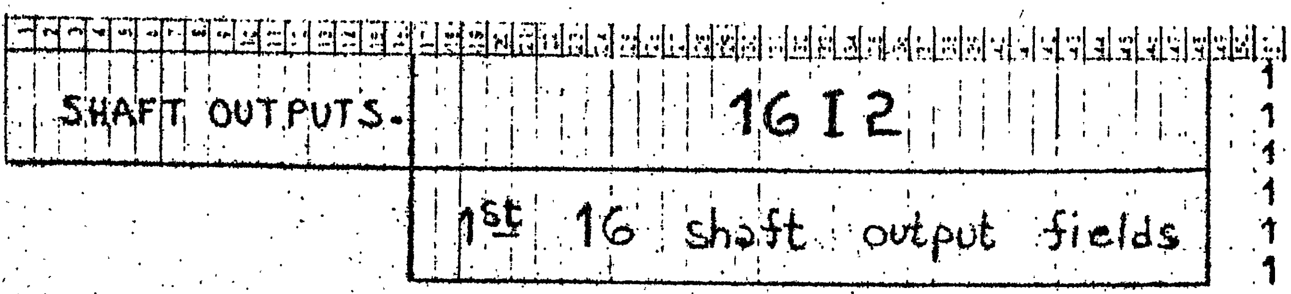
Class 5 S.M. data consists of a single output-variable specification card, if the compact (original SCE; single-card-always) format is used. In this case, interpretation is as follows:



But if the alternate expanded format is used for Class 5 S.M. data, then the first (of possibly more than one) card is interpreted as follows:

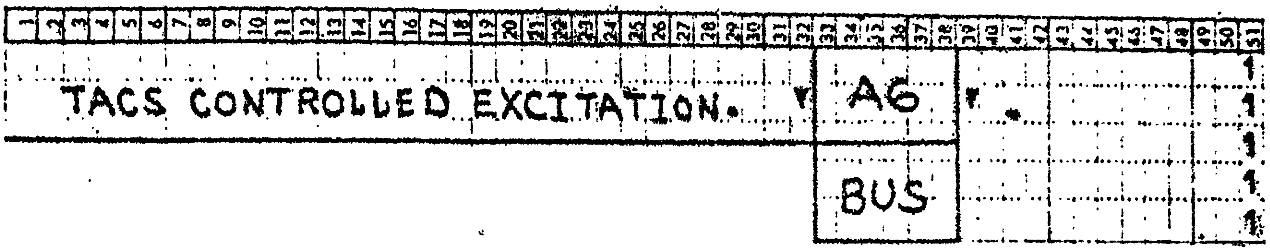


Provided the variable "TEXT" of the just-described card is equal to "EXTEND", then a second card is required for Class 5 S.M. data. Interpretat of this second card is as follows:

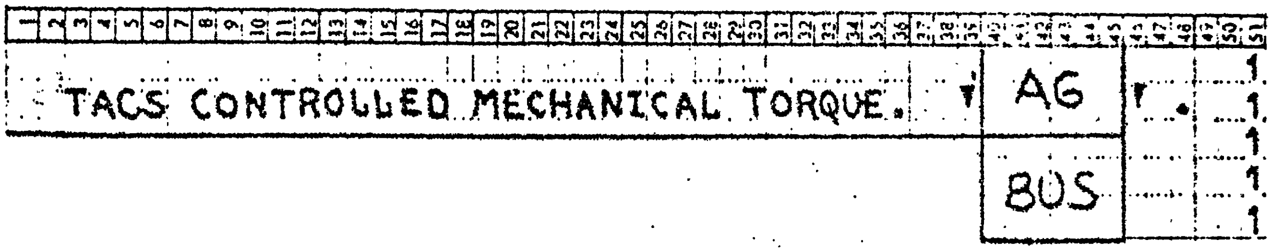


Class 6 S.M data consists of an indeterminate number of cards which describe any interface connections which are to exist between the machine and TACS. Columns 1-2 of such cards are punched with an integer "KK", and "BUS" (the name of a TACS variable) is A6 information of columns 3-8.

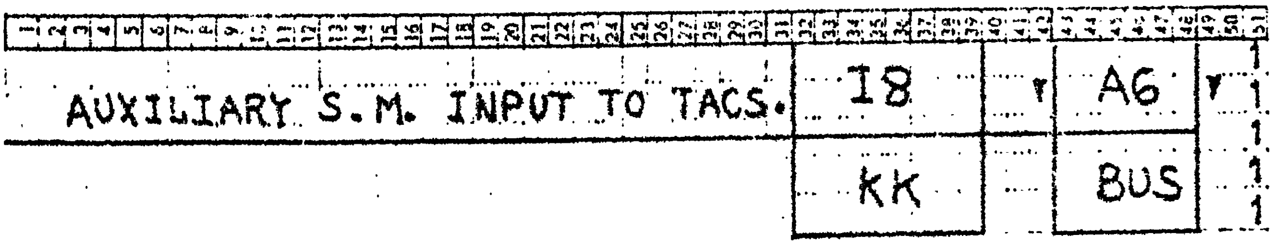
For "KK" equal to 71, the exciter connection is being specified, with interpretation as follows:



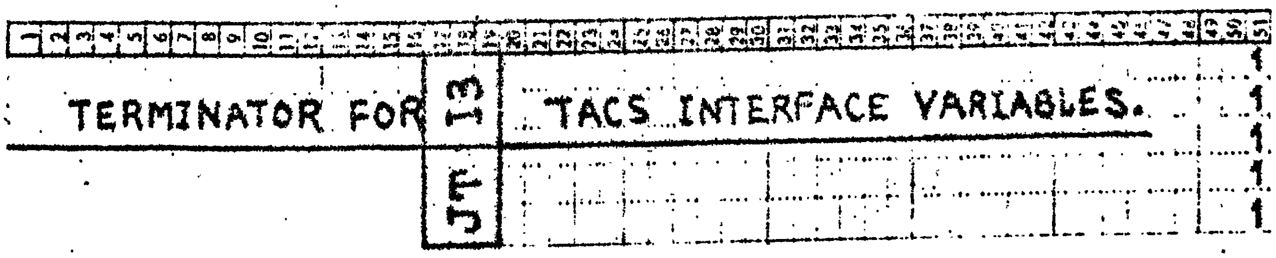
For "KK" equal to 72, the prime mover connection is being specified, with interpretation as follows:



For all other "KK" values (73, 74, or unity through 3*LIMASS), S.M. variables are to be passed from the machine to TACS sources. For all such cases, there is a single uniform interpretation, which follows:



For "KK" equal to zero and "FINISH" punched in columns 3-8, one has the bounding record which ends Class 6 data. Letting "JT" stand for the total number of preceding Class 6 data cards, interpretation of this final bounding record is then:



(13b) Universal Machine (U.M.) Model (Section 1.63)

The U.M. data cards are announced as an EMTP source of type 19 (punched in columns 1-2). Nothing else is required on this lead card, whose interpretation shows the number of cells of List 25 storage which are actually being used by the U.M. tables. Recall that "ABSOLUTE U.M. DIMENSIONS" of Section 1.0e13 determines this:

U.M. DATA BEGINS. LIST-25 CELLS USED =	I5	
	L25	

Next comes the data card bearing nothing by data flag INPU , which chooses between per unit and physical units for the input data:

BEGIN U.M. INPU =	I5	
	INPU	

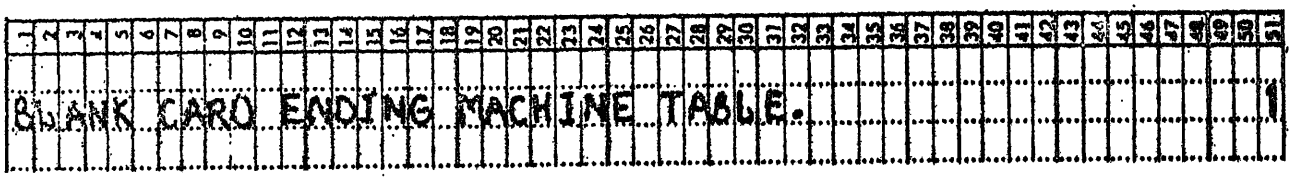
Next comes the "machine table", which will have a triplet of data cards for each U.M. component that is being used. The apparently inane reference to "card split" in the interpretations below has an historical explanation only (originally Hian used a single READ statement which covered the three data cards; when calls to CIMAGE were used, this had to be split into three separate READ statements). Symbols JSD and JSQ are abbreviations for JSATD and JSATQ, respectively. The three interpretations are as follows:

FIRST OF CARD SPLIT.	I5	I5	I5	
	JTYPE	NCLD	NCLQ	

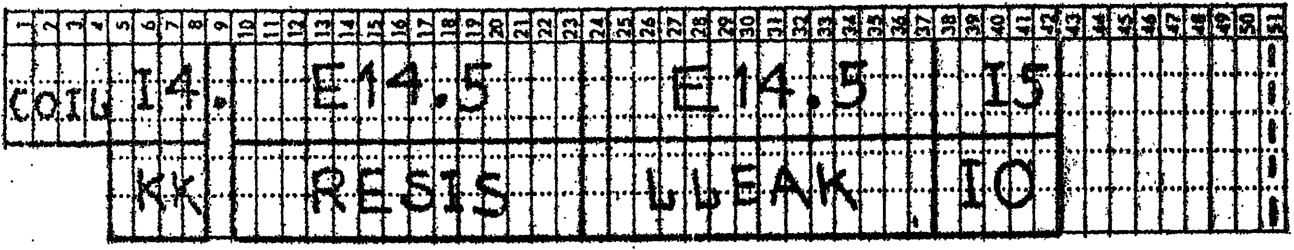
2ND OF SPLIT.	E14.5	E14.5	I5	
	OMEGM	LMUD	JSD	

3RD OF SPLIT.	E14.5	E14.5	I5	
	THETAM	LMUQ	JSQ	

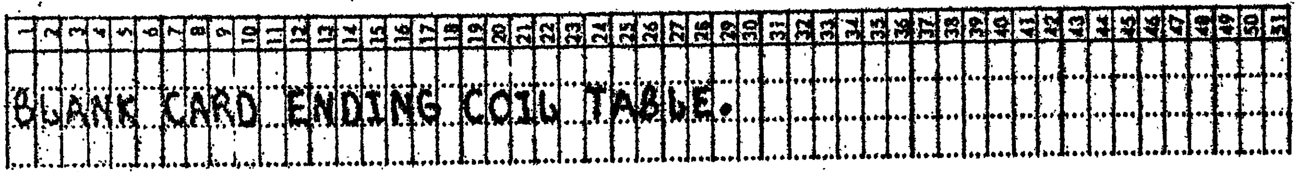
Such triplets of machine-specifications continue until they are terminated by a blank card, which is interpreted as follows:



Then come the coil cards, one for each coil of all U.M. components, in order. Using the abbreviation IO = CURQUT for the output request flag, interpretation of the card for coil KK is as follows:



The last such U.M. coil card is followed by a terminating blank card, which is interpreted as follows. This completes the U.M. data input, and control returns to "OVER5" source input.

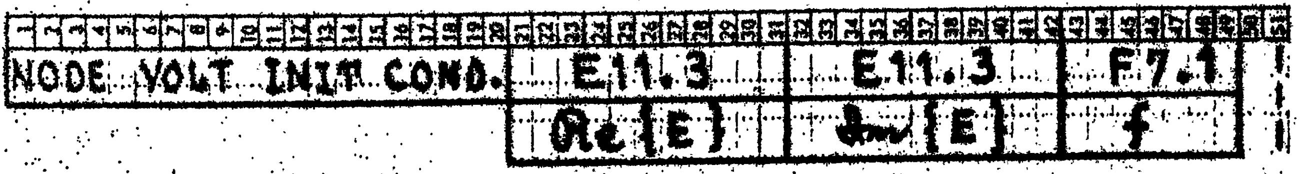


⑭ Over-riding Initial Conditions (Section 1.7)

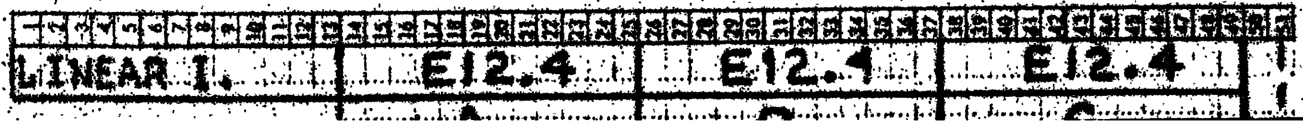
Because the initial-condition capability of the EMTP is far from complete, the explanation provided here shall likewise amount to little more than a documentation of those initial condition cards which are honored.

First, there are the original three classes of initial condition input, as per the subdivisions under Point b) of Section 1.7. These are node voltages, linear branches, and nonlinear branches (type code ID = 2, 3, and 4, respectively):

Cards for inputting node voltages come first (with "2" punched in columns 1-2, field ID), and are interpreted as follows. Only the first such card actually has the third field (frequency f) actually printed.



Next come the cards specifying currents in linear branches, with ID of 3. For lumped series R-L-C , or for Pi-equivalents, the interpretation is as follows:



For distributed-parameter branches, the program prints the following for the 2nd and later conductors, if any; the first is interpreted as a "LINEAR I." card as documented immediately above.

DISTRIB. I.	E12.4	E12.4	E12.4
	$Re\{I_k\}$	$Im\{I_k\}$	$Re\{I_m\}$

Finally, there is the interpretation of the cards for nonlinear and time-varying branches (ID of 4, punched in columns 1-2 of the card):

NONLIN. BRANCH INIT COND.	E11.3	E11.3
	i_{km}	ψ_{km}

The Type-96 hysteretic inductor is an exception to this general rule for nonlinear elements in that there are two additional cards which follow the initial one just described. Call these cards 2 and 3. Card 2 is punched with two integers and four floating point numbers, reading from left to right. The integers and first two floating point numbers appear in the interpretation of card 2:

TYPE-96.	I4	I4	E15.6	E15.6
	N15	N16	VCHAR(N17)	VCHAR(N17+1)

Card 3 is punched with one integer and four floating point numbers; th integer and first two floating-point numbers are part of the interpretation, which appears as follows:

TYPE-96.	I8	E15.6	E15.6
	N20	VCHAR(N18)	VCHAR(N19)

No further explanation of this Type-96 hysteretic inductor shall be provided, since such initial conditions should always be EMTP-punched rather than user-punched, and understanding is not actually required.

In the case of EMTP-punched terminal conditions which are re-used as EMTP initial conditions, there also is an extra class of cards (in addition to those listed above), for switches. There is one such card for each switch, with type code ID = 5 . Each such card carries two bus names (2A6 format, to identify switch), three integers (3I4), and four floating-point variables (4E13.6). Interpretation only uses the first three integers and the first floating-point variable:

45d-1

SWITCH INIT. COND.	I6	I6	I6	E13.4	
	N1	N2	N3	D1	

⑮ Output Specification Cards (Section 1.8)

Solution node voltages which are to be printed or plotted as functions of time are defined on one or more cards as per Section 1.8a. If the user requests all node voltage outputs by means of a 1-punch in column 2, the interpretation is:

REQUEST FOR OUTPUT OF ALL NODE VOLTAGES.	1

But for the usual case of selective voltage output, each card is interpreted by:

CARD OF BUS NAMES FOR NODE-VOLTAGE OUTPUT.	1

The preceding records were for deterministic (i.e., non-statistical) data cases, in accord with Section 1.8a . But for a "STATISTICS" data case, the separate, special specification of Section 1.8b applies. Here only selective output requests are allowed. Depending upon whether node voltage or voltage difference ("branch voltage" for short) outputs are being requested, interpretation is as p r one of the following:

Node voltage requests, "STATISTICS"

STATISTICAL OUTPUT OF NODE VOLTAGES.	E11.3
	BASEV

Voltage-difference requests, "STATISTICS"

STATISTICAL OUTPUT OF BRANCH VOLTAGES.	E11.3
	BASEV

(16) Cards for Batch-Mode Plotting (Section 1.10)

The card of 78-character case-title text, Point 1 of Section 1.10-B, is interpreted as follows:

PLOT CASE-TITLE TEXT.	1

Cards defining the graph subtitle text of Point 2 are interpreted as follows, assuming that the user has not attempted to input more than the limit of four for any one plot:

PLOT SUBTITLE CARD.	1

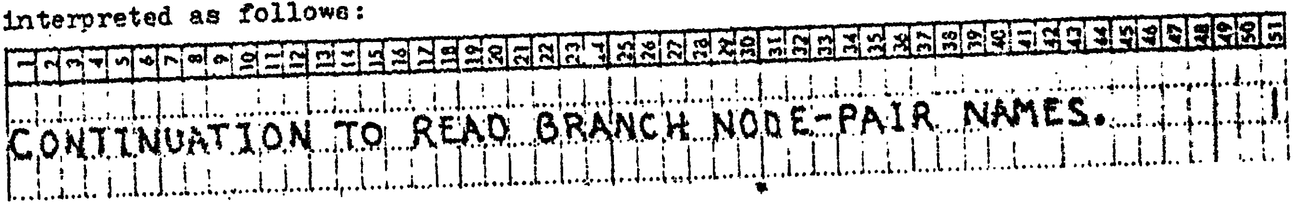
Excess graph subtitle-text cards (in excess of four) are simply ignored by the EMTP; they are given the following interpretation:

OVERFLOW SUBTITLE CARD DISCARDED	1

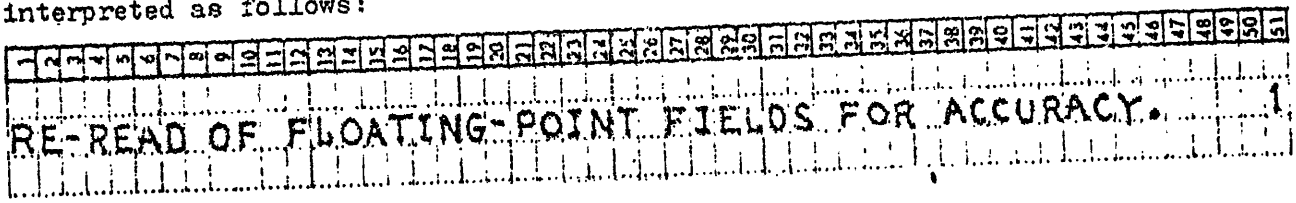
A plot specification card of Point 3 is interpreted as follows:

** PLOT CARD.	E11.3	E11.3	E11.3
	HPI	HMIN	HMAX

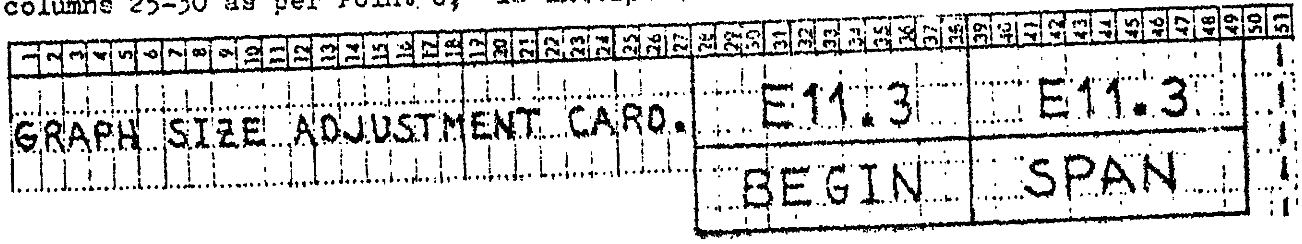
The extra "continuation card" of Point 4, for the input of 3 or 4 branch-variable node-pair identifications (six or eight node names), is interpreted as follows:



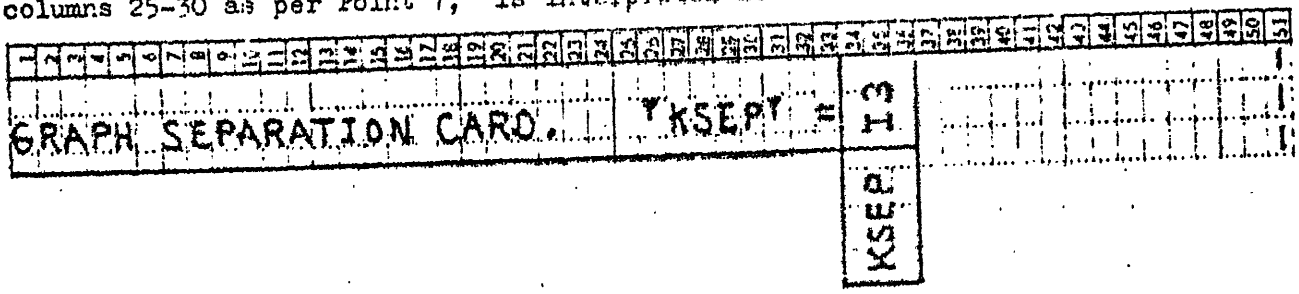
The extra "continuation card" of Point 5, for re-reading of the five floating-point parameters of the plot-specification card using 5E16.0 format, is interpreted as follows:



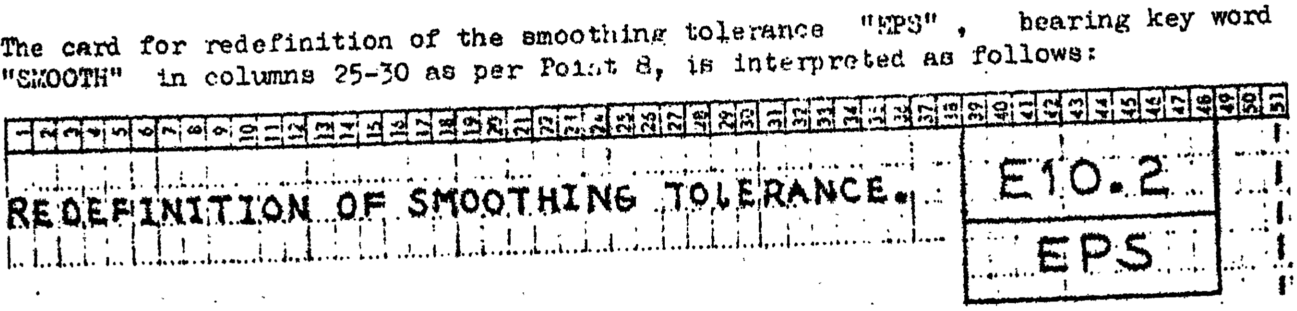
The card for Calcomp graph-size adjustment, bearing key word "HEIGHT" in columns 25-30 as per Point 6, is interpreted as follows:



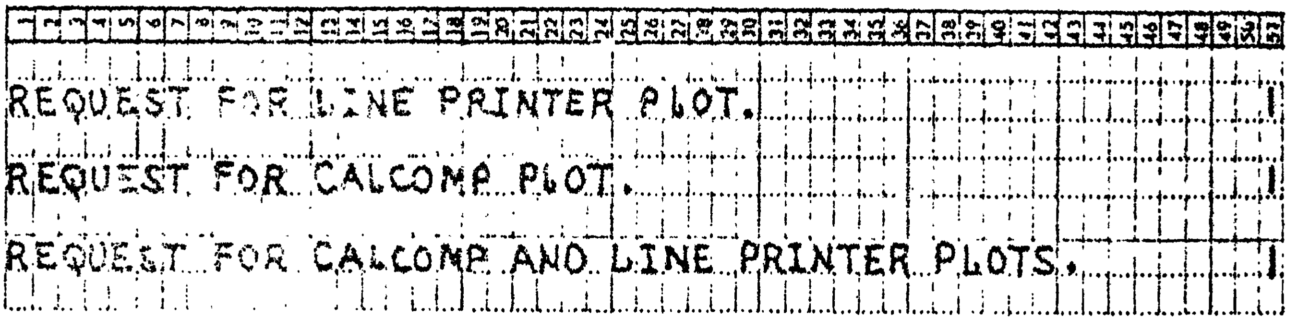
The card for Calcomp graph-separation adjustment, with key word "MARGIN" in columns 25-30 as per Point 7, is interpreted as follows:



The card for redefinition of the smoothing tolerance "EPS", bearing key word "SMOOTH" in columns 25-30 as per Point 8, is interpreted as follows:

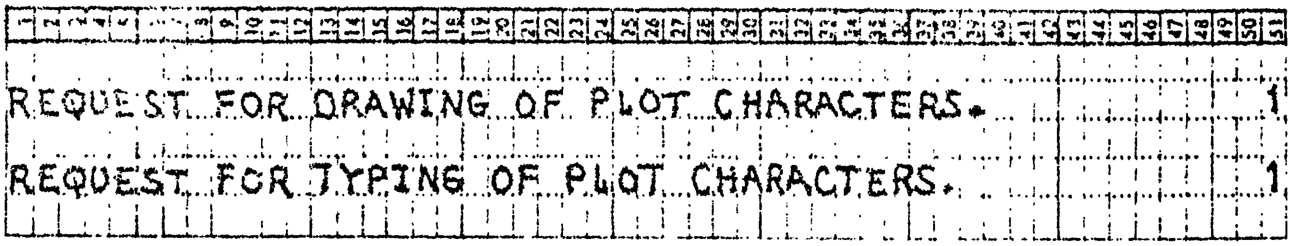


Batch-mode plotting can be done on either the line printer, or the Calcomp pen-and-ink plotter, or both, for any given plot. The three request cards of Point 9 allow for changing this graph mode selection by use of the three key words "PRINTER PLOT" , "CALCOMP PLOT" , and "CALCOMP PRINTER" . Interpretation for these three cards is as follows:



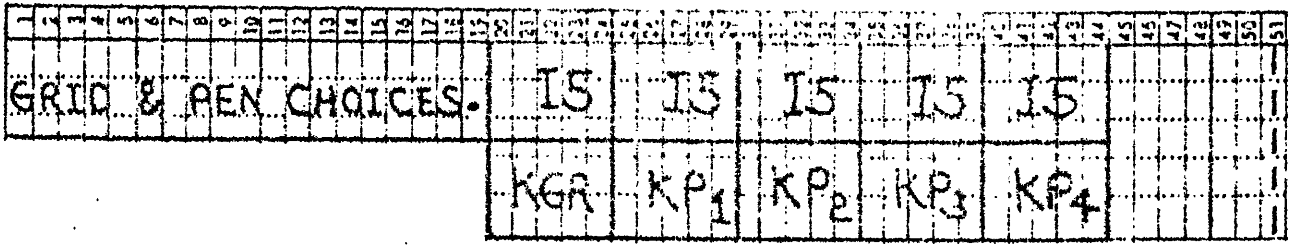
```
REQUEST FOR LINE PRINTER PLOT.                      1
REQUEST FOR CALCOMP PLOT.                           1
REQUEST FOR CALCOMP AND LINE PRINTER PLOTS.         1
```

There are two possible cards for changing the status of the plotter print-head, employing the key words "PRINT HEAD OFF" and "PRINT HEAD ON" . These are as per Point 10, and are given the following interpretations:



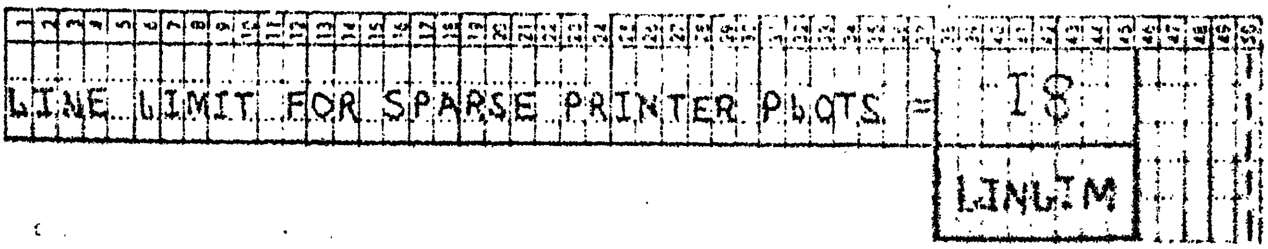
```
REQUEST FOR DRAWING OF PLOT CHARACTERS.             1
REQUEST FOR TYPING OF PLOT CHARACTERS.              1
```

With CalComp plotting, there is a choice of several different plotter pens, and the EMTP allows the user to specify these both for the background grid and also for the first four curves of a graph. This is via the "PEN CHOICE" request of Point 11, which reads five pen numbers. All five of these integers are confirmed in the data card interpretation:



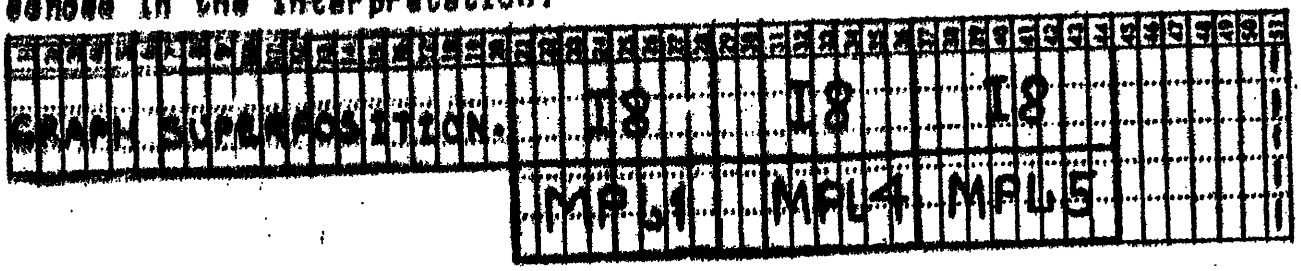
```
GRID & PEN CHOICES.  I5   I5   I5   I5   I5         1
                     KGR  KP1  KP2  KP3  KP4        1
```

For printer (character) plots, there is redefintion of the line limit for sparse plots via the "PLOT LINE LIMIT" request of Point 12. Interpretation confirms the new line limit "LINLIM" :

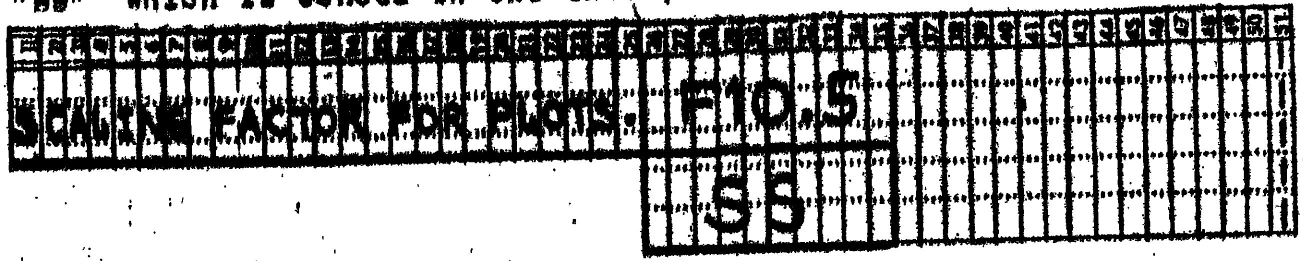


```
LINE LIMIT FOR SPARSE PRINTER PLOTS =   I8         1
                                        LINLIM     1
```

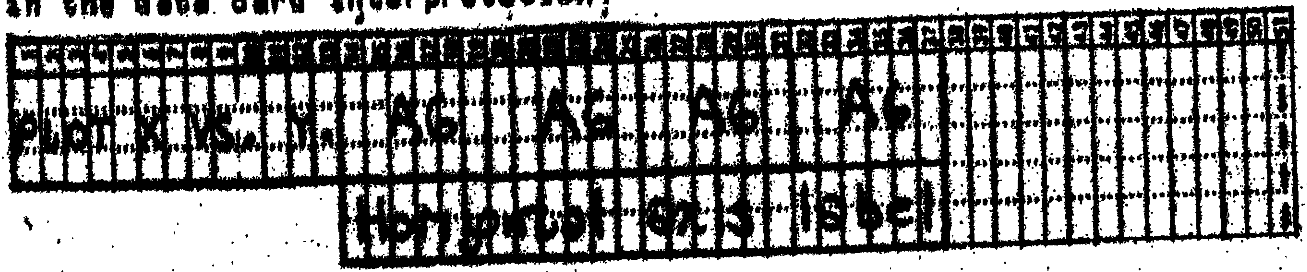
For CalComp plots, there is the option of superimposing more than one plot on top of each other, thanks to the "SUPERIMPOSE" request of Point 13. The request card bears three integers, which are all echoed in the interpretation:



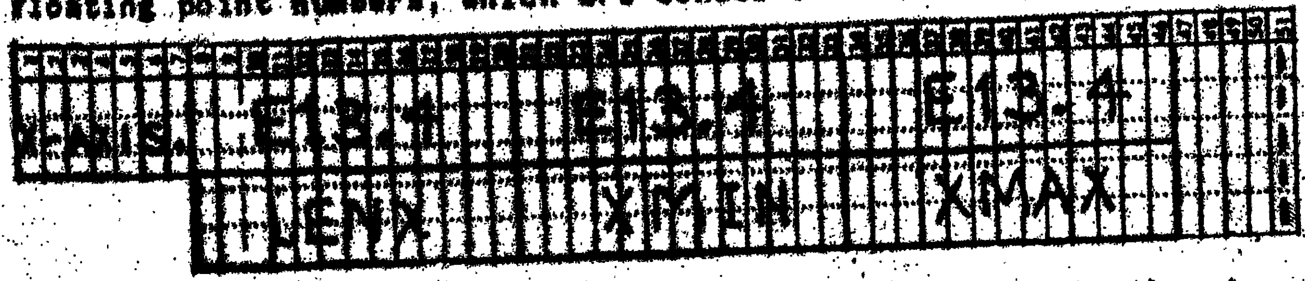
For CalComp plots, there is the option of photographic magnification or reduction of a plot image, thanks to the "SCALE" request of Point 14. The request card bears a single floating-point parameter "SS" which is echoed in the interpretation:



For Calcomp plots, it is possible to plot one EMTP variable against another, thanks to the "X-Y PLOT" request of Point 15. Three data cards are involved. The first of these bears the just-stated request word, along with a 24-character horizontal axis label, which is echoed in the data card interpretation:



Next comes a data card for the horizontal ("X") axis, bearing three floating point numbers, which are echoed in the interpretation:



Finally there is a corresponding card for the vertical ("Y") axis, though it also bears fourth and fifth parameters which do not appear in the interpretation:

Y-AXIS. E13.4 E13.4 E13.4

LENY YMIN YMAX

The plot specification card of Point b-2 is interpreted as follows:

PLOT CARD.

(17) Blank termination cards

Various classes of data are terminated by blank cards. Any blank card so read is interpreted as such, with an approrriate message telling what the blank card has signalled the end of. All of these are shown below, in the order that they would be encountered in a data case. Note that:

a) The first 5 are associated with TACS data (if any).

b) Number 9 will not be present if the user requests the output of all node voltages (by means of a "1"-punch in column 2). For a "STATISTICS" or "SYSTEMATIC" data case, this card would pertain to the base-cas solution only, in any event.

c) Number 11 exists only for a "STATISTICS" or "SYSTEMATIC" data case.

d) Number 12, which stops execution of the EMTP, is actually the first card of the following (nonexistant data case.

```
1)  BLANK CARD TERMINATING TACS FUNCTION BLOCKS.       1
2)  BLANK CARD TERMINATING TACS SOURCE CARDS.          1
3)  BLANK CARD TERMINATING TACS SUPPL. VAR. CARDS.     1
4)  BLANK CARD TERMINATING OUTPUT VARIABLE REQUESTS    1
5)  BLANK CARD TERMINATING TACS INIT. CONDIT. CARDS.   1
                                                       1
6)  BLANK CARD TERMINATING BRANCH CARDS.               1
7)  BLANK CARD TERMINATING SWITCH CARDS.               1
8)  BLANK CARD TERMINATING SOURCE CARDS.               1
9)  BLANK CARD ENDING NODE NAMES FOR VOLTAGE OUTPUT.   1
10) BLANK CARD TERMINATING PLOT SPEC. CARDS.           1
11) BLANK CARD TERMINATING STATISTICS OUTPUT CARDS.    1
12) BLANK TERMINATION-OF-RUN CARD.                     1
```

⑱ __Supporting Routine Printout__ (Section 7.)

As described in Section 7. , certain supporting routines have been incorporated into the Transients Program structure. These have their own printout, which shall not be described here. In general, comment cards can be used with these routines, and input card images are printed out for the user, as with the Transients Program proper.

2.2 FORMAT OF PRINTED, COMPUTED RESULTS

In addition to just listing and interpreting the input data as per the preceding section, printed output of numerous different sorts can be generated by the Transients Program. Only the most important of these classes will be listed in this section.

2.2a Printed Transients Solution Variables.

As controlled by integer miscellaneous data parameter "IOUT" (see Section 1.0h), selected variables of the transient solution are outputted to the line printer every IOUT-th time-step point. This frequency can be altered as the solution progresses, if desired (see Section 1.1b). Characteristics of this time-step-loop output include the following points:

Point 1: Variables are printed out in a fixed order, time-step by time-step, as the solution is advanced. Column headings at the start identify all output variables which will be printed.

Point 2: The time-step number and also the time corresponding to each batch of values begins on the extreme left of the page, beneath the headings "STEP" and "TIME" .

Point 3: Immediately thereafter, on the same line, all node voltages requested for output (see Section 1.H) are printed. These are identified by a heading bearing the node names in question. In number, such columns are noted by the message "FIRST XX OUTPUT VARIABLES ARE ELECTRIC-NETWORK NODE VOLTAGES (WITH RESPECT TO LOCAL GROUND);" which precedes the heading. Here "XX" is an integer. If over 9 node voltage outputs exist, printing continues on the line or lines immediately following.

Point 4: Immediately to the right of the last node voltage will come all branch voltages or branch powers (as requested by column-80 punches on the branch cards in question), identified by the pair of terminal node names. The two node names are printed one above the other; if K is the top node, and M is the lower node, then three types of output are possible within this class:

a) Voltage difference, $v_{km} = v_k - v_m$.

b) For switches, "power output" always represents power flow through the switch, from K to M : $P = P_{km}$

c) For all nonswitch branches, "power output" always represents the loss, input, or dissipation. This is $P = P_{km} + P_{mk}$.

In number, such columns are noted by the message

> "NEXT XX OUTPUT VARIABLES ARE BRANCH VOLTAGES (VOLTAGE OF UPPER NODE MINUS VOLTAGE OF LOWER NODE);"

which appears immediately below the similar message for node voltages. As with node voltages, continuation on as many lines as necessary is automatically provided.

Point 5: Immediately to the right of the last branch voltage or power will come all branch currents or energies. The sign on flows is as just mentioned under Point 4, with again three types of output within this class:

a) Branch current i_{km} (from k to m, measured at end k).

b) For switches, "energy output" always represents the flow of energy through the switch, from k to m, since time zero:

$$E(t) = \int_0^t P_{km}(u)\,du$$

c) For all nonswitch branches, "energy output" always represents the loss, input, or dissipation within [illegible]

$$E(t) = \int_0^t \left\{ P_{km}(u) + P_{mk}(u) \right\} du$$

In number, such columns are noted by the message

"NEXT XX OUTPUT VARIABLES ARE BRANCH CURRENTS (FLOWING FROM THE UPPER NODE TO THE LOWER)"

which appears immediately below the similar message for branch voltages and powers. As with preceding variables, continuation on as many lines as necessary is automatically provided.

Point 6: Immediately to the right of the last branch current or energy will come all dynamic synchronous machine (S.M.) output variables. Various types of variables are possible (angles, torques, currents, etc.), as fully explained in Section V.G under class 5 data. A pair of 6-character names is used for identification, with the first (upper) one always identifying the machine in question (e.g., "MACH 3" stands for the third S.M. component, in order of input). The second (lower) name identifies the variable type (e.g., "ANG 7" stands for the angle of the 7th mass of the shaft system). In number, such columns (of S.M. variables) are noted by the message

"NEXT XX OUTPUT VARIABLES PERTAIN TO DYNAMIC SYNCHRONOUS MACHINES, WITH NAMES GENERATED INTERNALLY;"

which appears immediately below the similar message for branch currents. As with preceding variables, continuation on as many lines as necessary is automatically provided for.

Point 7: Immediately to the right of the last S.M. variable will come all TACS output variables. These were requested using data cards as are described in Section B.5.6. A pair of 6-character alphanumeric names is used for identification of each variable, with the first (upper) name always being "TACS ". The second (lower) name is simply the name of the TACS variable in question. In number, such TACS variable columns are noted by the message

"FINAL XX OUTPUT VARIABLES BELONG TO 'TACS' (NOTE INTERNALLY-ADDED UPPER NAME OF PAIR),"

which appears immediately below the similar message for dynamic S.M. variables. As with preceding variables, continuation on as many lines as necessary is automatically provided for.

Sample Illustrative Output

```
CARD OF BUS NAMES FOR NODE-VOLTAGE OUTPUT.        I  NAVH ANAVH BNAVH C
BLANK CARD ENDING NODE NAMES FOR VOLTAGE OUTPUT.  I

COLUMN HEADINGS FOR THE  16  EMTP OUTPUT VARIABLES FOLLOW.   THESE ARE ORDERED ACCORDING TO THE FIVE
POSSIBLE EMTP OUTPUT-VARIABLE CLASSES, AS FOLLOWS ....
   FIRST   3  OUTPUT VARIABLES ARE ELECTRIC-NETWORK NODE VOLTAGES (WITH RESPECT TO LOCAL GROUND)I
    NEXT   3  OUTPUT VARIABLES ARE BRANCH VOLTAGES (VOLTAGE OF UPPER NODE MINUS VOLTAGE OF LOWER NODE)I
    NEXT   3  OUTPUT VARIABLES ARE BRANCH CURRENTS (FLOWING FROM THE UPPER EMTP NODE TO THE LOWER)I
    NEXT   7  OUTPUT VARIABLES PERTAIN TO DYNAMIC SYNCHRONOUS MACHINES, WITH NAMES GENERATED INTERNALLY)
   FINAL   0  OUTPUT VARIABLES BELONG TO  "TACS"  (NOTE INTERNALLY-ADDED UPPER NAME OF PAIR).
BRANCH POWER  CONSUMPTION (POWER  FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH VOLTAGE FOR THIS GROUPING)
BRANCH ENERGY CONSUMPTION (ENERGY FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH CURRENT FOR THIS GROUPING.
                                                          MCC1 A       MCC1 B        MUD1 C        GEN  A        GEN  B      GEN  C
 STEP    TIME        NAVH A        NAVH B        NAVH C   MCC2 A       MUD2 B        MOD2 C        NAVL A        NAVL B      NAVL C

                     MACH 1        MACH 1        MACH 1        MACH 1       MACH 1        MACH 1        MACH 1
                     TQ GEN        VEL 5         TQS 12        TQS 13       TQS 34        TQS 45        TQS 56
                                                                 SWITCH "GEN  A" TO "NAVL A" CLOS[illegible]
***                                                              SWITCH "GEN  B" TO "NAVL B" CLOSED AFTER [illegible]
***                                                              SWITCH "GEN  C" TO "NAVL C" CLOSED AFTER [illegible]
***                                                              SWITCH "SHT  A" TO [illegible]   " CLOSED AFTER [illegible]
***                                                              SWITCH "SHT  B" TO [illegible]   " CLOSED AFTER [illegible]
***                                                              SWITCH "SHT  C" TO [illegible]   " CLOSED AFTER [illegible]
***
     0  0.000000   .841213E+05 -.384968E+06  .330447E+06 -.[illegible]   .[illegible]   .[illegible]   .0  [illegible]
                   .900310E+00   .0          .270435E+00  .[illegible]   .704361E+00   .902950E+00   .894095E+0[illegible]
```

Etc. ⋮

2.2b Non-fatal error, warning, or otherwise-informative messages

The printed EMTP output may include various messages which remind the user of special situations which have occurred during the solution, situations which the user should generally note and think about. In general, the situations in question are peculiar to the data case at hand, and will be news to the user.

Special mention should perhaps be made of conventional switching or flashover operations, which have been excluded from the tabulation of the present section. Such operations are important enough so as to be listed separately, in Section 2.2c .

A photo-reduced listing of all such EMTP informative messages will be found on the pages which immediately follow. Each message has been coded with a number, it will be noted. Added explanation of these line-printer messages then follows, as regular typewritten text. It is the sort of general verbal explantion which Program Maintenance might provide for a user, in case of an academic (i.e., non-specific) inquiry.

```
1.  ---- WARNING.   NONZERO MISC. DATA PARAMETER  'XOPT'  IS DIFFERENT THAN ☐ HZ.   THIS IS UNUSUAL.
         A VALUE OF ☐ WAS READ FROM COLUMNS 17-24 OF THE DATA CARD JUST READ.   EXECUTION WILL CONTINUE USING
         THIS VALUE, AS SUSPICIOUS AS IT SEEMS TO THE T.P.

2.  ---- WARNING.   NONZERO MISC. DATA PARAMETER  'COPT'  IS DIFFERENT THAN ☐ HZ.   THIS IS UNUSUAL.
         A VALUE OF ☐ WAS READ FROM COLUMNS 25-32 OF THE DATA CARD JUST READ.   EXECUTION WILL CONTINUE USING
         THIS VALUE, AS SUSPICIOUS AS IT SEEMS TO THE T.P.

3.  HIGH RES. ADDED AT T.P. ACROSS TYPE-99 ELEM.      1 0☐☐        ☐
    HIGH RES. ADDED AT T.P. ACROSS SYN.M. MAGN.       1 0☐☐        ☐

4.  REMEMBER ---- WHAT ARE LABELED AS THE INITIAL ☐ BRANCH-OUTPUT CURRENTS ARE IN REALITY KARRENBAUER
                  MODAL VOLTAGES AT THE TWO ENDS OF THE LAST DISTRIBUTED-PARAMETER LINE OF THE DATA CASE BEING SOLVED.
    ------------- THE FIRST ☐ MODE VOLTAGES AT THE  'BUS1'  END ALL COME FIRST, FOLLOWED BY ALL THE CORRESPONDING
                  ENTRIES FOR THE  'BUS2'  END OF THE LINE.

5.  NOTE ---- THE PRECEDING PRINTOUT SHOWS THAT GROUND WAS NOT RENUMBERED FIRST IN THE TRANSIENT-NETWORK RENUMBERING.
              WE WILL SWAP THE NEW NUMBERS BETWEEN GROUND AND WHATEVER NODE WAS RENUMBERED FIRST, IN ORDER TO GET A CONSISTENT
              NUMBERING FOR THE REST OF THE T.P. CALCULATIONS.

6.  NONLINEAR AND TIME-VARYING RESISTANCES IGNORED IN STEADY STATE SOLUTION.  NONLINEAR INDUCTANCES INCLUDED WITH LINEAR PART

7.  COMMENT ---- NO SINUSOIDAL SOURCES REQUESTED FOR STEADY-STATE SOLUTION.   THUS THIS SOLUTION IS BYPASSED.

8.  NOTICE. ---- TWO OR MORE SINUSOIDAL VOLTAGE SOURCES ARE PRESENT ON NODE '☐' DURING THE STEADY-STATE
                 SOLUTION.   AS PER THE USER'S MANUAL, THESE VOLTAGES WILL ALL BE ADDED TOGETHER TO GET A TOTAL NODE VALUE.

9.  NOTE. ---- NODE '☐' HAS BOTH VOLTAGE AND CURRENT SOURCES ON IT.   THE CURRENT SOURCE HAS NO EFFECT
               ON THE SOLUTION, THEN, AND COULD BE OMITTED.

10. WARNING. ---- SOURCE NUMBER ☐ ON BUS '☐' WILL NOT BE PRESENT DURING THE
                  STEADY-STATE PHASOR NETWORK SOLUTION FOR INITIAL CONDITIONS.   THE SOURCE FREQUENCY OF ☐ DIFFERS FROM THE
                  ASSUMED SOLUTION FREQUENCY OF ☐ HZ BY OVER ONE PERCENT.   DID THE USER MEAN THIS.  THE T.P. WONDERS.

11. CAUTION. ---- DURING Y-MATRIX ELIMINATION FOR STEADY-STATE SOLUTION VOLTAGES, A NEAR-ZERO DIAGONAL ELEMENT
                  FOR NODE '☐' EXISTS JUST BEFORE RECIPROCATION.   USING MAGNITUDES SQUARED FOR ALL 3 QUANTITIES, WE HAVE
                  ORIGINAL DIAGONAL VALUE = ☐,   QUESTIONABLE VALUE = ☐,   TOLERANCE RATIO = ☐.
                  THE NODE IN QUESTION MAY BE CONNECTED TO OTHER NODES, FORMING A SUBNETWORK.   BUT THE SUBNETWORK HAS NO OR
                  VERY WEAK PATH TO GROUND OR OTHER KNOWN-VOLTAGE NODE IN THE STEADY-STATE.   SOLUTION VOLTAGES OF THIS
                  SUBNETWORK WILL ALL BE SET TO ZERO.

12.     REQUESTED OUTPUT FOR NONEXISTENT NODE '☐'  WILL BE IGNORED.

13. STEADY-STATE PHASOR SOLUTION IS IDENTICALLY ZERO.   THERE ARE NO NONZERO VALUES TO BE OUTPUTTED, SINCE
    NO SINUSOIDAL SOURCES WERE PRESENT FOR TIME LESS THAN ZERO.
```

14. NOTE. ---- THIS FUNCTION BLOCK HAS THE TACS VARIABLE '☐' INPUTTED AN EVEN NUMBER OF TIMES, WITH THE NET RESULT BEING CANCELLATION TO ZERO. ALL INPUTS NAMED '☐' ARE THUS GOING TO BE IGNORED BY THE EMTP, FOR THIS PARTICULAR TACS FUNCTION BLOCK. DID THE USER REALLY INTEND THAT THIS BE THE CASE, THE EMTP WONDERS.

15. RESIDUAL FLUX OF SWITCHED-L ELEMENT '☐' TO '☐' = ☐
INITIAL FLUX IN COIL '☐' TO '☐' = ☐
WARNING. ASSUMPTION THAT AC STEADY STATE HAS FUNDAMENTAL FREQUENCY ONLY IS QUESTIONABLE WITH PRECEDING FLUX OUTSIDE LINEAR REGION

16. OBSERVATION. ---- THE FIRST CONDUCTOR OF A ☐-CONDUCTOR DISTRIBUTED-PARAMETER LINE CONNECTS BUS '☐' WITH BUS '☐'. THE PRESENT CASE HAS ZERO INITIAL CONDITIONS, AND ALSO A STUDY-TERMINATION TIME 'TMAX' WHICH IS LESS THAN THE TRAVEL TIME FOR THIS LINE. HENCE NO STORAGE OF PAST-HISTORY POINTS IS REQUIRED FOR THIS LINE (I.E., THIS LINE DOES NOT ADD TO THE SIZE OF THE LIST-6 ARRAYS IN THE CASE-TERMINATION STATISTICS).

17. ☐ OUT OF ☐ SWITCH CLOSING TIMES FALLING BEYOND ☐ TIMES THE STANDARD DEVIATION.

18. TROUBLE AT TIME IN TYPE-99 OR-98 ELEM NUMBER ☐ ☐ ☐ ☐

19. REQUEST FOR VOLTAGE OUTPUT OF NONEXISTENT NODE '☐' WILL BE IGNORED.

20. WARNING. YOUR INITIAL CONDITION ON '   ' WILL BE IGNORED AND RECALCULATED BY THE TACS STEADY-STATE ROUTINE.

21. PUNCHING OF CURRENTS STOPPED BECAUSE INFORMATION IS INSUFFICIENT IN THE PRESENCE OF DISTRIBUTED PARAMETERS

** LOOK, LOOK **

22. DURING THIS RUN, A TOTAL OF ☐ RANDOM SWITCH CLOSINGS LESS THAN TIME ZERO WERE GENERATED BY THE RANDOM NUMBER GENERATOR. BUT THE T.P. HAS NO WAY OF HANDLING SUCH CLOSURES. ALL SUCH ILLEGAL CLOSING TIMES WERE CONVERTED TO TIME ZERO (THEY SHOULD SHOW UP IN THE PRINTOUT THAT WAY) FOR SIMULATION PURPOSES. THE IMPLICATIONS OF THIS MODIFICATION SHOULD BE UNDERSTOOD BY THE USER. IF IN ANY DOUBT, THE USER IS STRONGLY ADVISED TO SEEK EXPERIENCED COUNSEL ON THIS SUBJECT.

** LOOK, LOOK **

23. THE SPECIFIED GRAPH SEPARATION OF ☐ INCHES IS CONSIDERED TOO SMALL, AND IS RESET TO ☐ INCHES.

24. ****WARNING**** REQUESTED SMOOTHING TOLERANCE OF ☐ MAY CAUSE INACCURATE PLOT.

25. NOTE ---- THE REQUESTED BOTTOM MARGIN OF ☐ AND GRAPH HEIGHT OF ☐ REQUIRES A TOTAL PAPER HEIGHT OF ☐. THIS IS GREATER THAN THE HEIGHT SPECIFIED IN "CALL PAPRSZ", WHICH IS ☐ THE REQUESTED VALUES WILL BE IGNORED AND THE LAST SPECIFIED (OR DEFAULT IF NO HEIGHT VALUES WERE EVER GIVEN) WILL BE USED.

26. NOTE ----- A TIME SCALE OF ☐ WAS READ FROM COLUMNS 5-7 OF THE PRECEDING PLOT REQUEST CARD. TOGETHER WITH THE REQUESTED MINIMUM OF ☐ UNITS (READ FROM COLUMNS 8-11) AND REQUESTED MAXIMUM OF ☐ UNITS (READ FROM COLUMNS 12-15), THIS IMPLIES A PLOT OF LENGTH ☐, WHICH EXCEEDS THE CURRENTLY IMPOSED FLAT-BED LIMIT OF ☐ INCHES. THE SCALE ON THE TIME AXIS WILL BE CHANGED BY THE T.P. SO THAT THE SPECIFIED RANGE COVERS EXACTLY 12 INCHES OF PAPER. IF THE USER HAS QUESTIONS, CALL PROGRAM MAINTENANCE.

27. ACTUALLY, THE JUST-QUOTED PAPER HEIGHT IS THE PAPER HEIGHT MINUS THE OFFSET HEIGHT OF ☐ FOR THE ONE OR MORE GRAPHS WHICH HAVE ALREADY BEEN DRAWN VERTICALLY BELOW THE UPCOMING PLOT. THE USER SHOULD NOT INCREASE VERTICAL DIMENSIONS UNLESS HE IS AT THE BOTTOM OF THE PAPER, OR UNLESS HE IS SURE THAT HE HAS SUFFICIENT VERTICAL SPACE LEFT ON THE PAPER FOR AT LEAST ONE MORE PLOT. THE SIZE ADJUSTMENT REMAINS CANCELLED.

28. THE NUMBER SPECIFYING THE UNITS ON THE HORIZONTAL SCALE, PUNCHED IN COLUMN 4 OF THE PLOT REQUEST CARD, MUST BE BETWEEN 1 AND 5 (INCLUSIVE). THE NUMBER READ FORM THE LAST SUCH CARD WAS ☐. THIS PLOT REQUEST IS CANCELLED.

29. BUS NAME "☐" OF THE USER'S LAST-READ PLOT CARD IS NOT THE NAME OF A BUS HAVING NODE VOLTAGE OUTPUT. HENCE THIS FIELD WILL BE IGNORED BY THE T.P. (TREATED AS IF IT HAD BEEN BLANK). THE USER IS REMINDED THAT CORRECT SPELLING AND THE CONSISTENT POSITIONING OF ALL BLANKS WITHIN THE DATA FIELDS OF WIDTH 6 FOR ALL BUS NAMES IS REQUIRED.

30. THE USER'S LAST-READ PLOT CARD REQUESTS A PLOT FOR A BRANCH VARIABLE WHICH IS IDENTIFIED BY TERMINAL NAMES "☐" AND "☐". BUT THE T.P. CANNOT FIND THIS REQUESTED VARIABLE IN THE LIST OF OUTPUT VARIABLES, SO THIS PARTICULAR PLOT REQUEST MUST BE IGNORED. THE USER IS REMINDED THAT CORRECT SPELLING AND THE CONSISTENT POSITIONING OF ALL BLANKS WITHIN THE DATA FIELDS OF WIDTH 6 FOR ALL BUS NAMES IS REQUIRED. ALSO, THE USER SHOULD BE REMINDED THAT BRANCH-OUTPUT REQUESTS ARE MADE USING COLUMN-80 PUNCHES ON THE BRANCH CARDS IN QUESTION. THE USER SHOULD DOUBLE-CHECK THAT HE REALLY HAS REQUESTED THE OUTPUT VARIABLE WHICH HE IS TRYING TO PLOT (AND WHICH GOT HIM IN TROUBLE). ONE COMMON ERROR IS TO REQUEST ONLY BRANCH-CURRENT OUTPUT (A 1-PUNCH IN COLUMN 80) AND THEN TRY TO PLOT BRANCH VOLTAGE ---- OR VICE VERSA. FINALLY, THE USER SHOULD CHECK THAT BRANCH OUTPUT IS EVEN POSSIBLE FOR THE COMPONENT IN QUESTION, SINCE COLUMN-80 PUNCHES ARE BE IGNORED IF THE COMPONENT IN QUESTION DOES NOT PROVIDE FOR SUCH OUTPUT. ANY BRANCH-OUTPUT REQUEST FOR A MULTIPHASE DISTRIBUTED LINE FALLS INTO THIS CLASS, IT WILL BE NOTED.

31. PLOT CARD ERROR. TIME-AXIS SPECIFICATION IS ILLEGAL. THIS PLOT REQUEST IS BEING SKIPPED.
☐ ☐ ☐

32. NO VALID PLOT-VARIABLE NAME OR NAMES WAS PUNCHED ON THE USER'S LAST-READ PLOT CARD. HENCE THE T.P. WILL IGNORE THIS PLOT CARD COMPLETELY, AND GO ON TO READ THE NEXT ONE (FUN AND GAMES CONTINUE).

33. *** THE PLOTTING ARRAY EV HAS BEEN DIMENSIONED SUCH THAT THE WORKING SIZE IS ☐. THIS IS LESS THAN ☐ WHICH IS THE SIZE REQUIRED FOR THIS PLOT. THIS REQUEST IS CANCELLED.

34. NO PLOT POINTS FOUND BETWEE THE REQUESTED TIME LIMITS ________ TO ________ . THIS PLOT REQUEST CANCELLED.

35 WHILE SCANNING THE DATA POINTS FOR CURVES OF THE LAST-READ PLOT CARD, A NEED FOR SMOOTHING OF CURVE NUMBER ____ BEYOND TIME ________ SECONDS HAS BEEN DETERMINED. AT THIS POINT, ____ SUCCESSIVE, UNINTERRUPTED, ALTERNATING RELATIVE MAXIMA AND RELATIVE MINIMA HAVE BEEN OBSERVED. THIS IS TAKEN AS A SIGN OF A SPURIOUS MATHEMATICAL OSCILLATION, SOMETHING WHICH SHOULD NOT EXIST PHYSICALLY (AT LEAST NOT FOR AN INTELLIGENT USER WHO HAS PICKED THE TIME-STEP SIZE "DELTAT" AND THE OUTPUT FREQUENCY "IPLOT" PROPERLY). AT THIS POINT, THE OMNISCIENT AND OMNIPOTENT T.P. (OTHERWISE AFFECTIONATELY REFERRED TO AS "BIG BROTHER" BY THOSE USERS WHO ARE ACCUSTOMED TO HIS MODUS OPERANDI) HAS DECIDED TO SMOOTH THIS CURVE FOR ALL LATER TIME. THIS SMOOTHING INVOLVES SIMPLY THE AVERAGING OF SUCCESSIVE ORDINATES IN THE OUTPUT FILE OF PLOT-VARIABLE POINTS FOR THIS CURVE, BEFORE PLOTTING BEYOND THIS POINT IN TIME.

36. ****THE NUMBER OF LINES PRINTED FOR THIS PLOT REQUEST NOW EXCEEDS THE TOTAL NUMBER OF DATA POINTS.
****SINCE CALCOMP PLOT WAS ALSO SPECIFIED, ONLY PRINTER PLOT IS CANCELLED FOR THIS REQUEST.

37. ****THE NUMBER OF LINES PRINTED FOR THIS PLOT REQUEST NOW EXCEEDS THE TOTAL NUMBER OF DATA POINTS.
****SINCE ONLY PRINTER PLOT WAS SPECIFIED, THIS PLOT REQUEST IS CANCELLED.

38. WARNING. ---- THE LIMITS ON [illegible] WHICH APPLY TO THE TACS FUNCTION BLOCK WITH OUTPUT NAME '____' HAVE [illegible] AT TIME ________ SECONDS. [illegible] THAT IS, THE UPPER LIMIT IS [illegible] THE LOWER LIMIT, [illegible] STRANGE RESULTS MIGHT BE EXPECTED [illegible]. THERE SHALL BE [illegible] ALTHOUGH THE SIMULATION WILL CONTINUE, [illegible] NO WARNING MESSAGE [illegible] FOR ANY SUBSEQUENT CRISS-CROSSING OF THE LIMITS OF ANY TACS BLOCK.

39\.

40. NOTE. ---- THE USER HAS REQUESTED A TACS VARIABLE NAMED '____' FOR OUTPUT PURPOSES. THIS WAS NUMBER ____ IN ORDER OF INPUT, AS READ FROM THE TACS OUTPUT-VARIABLE SPECIFICATION CARDS. BUT THIS IS A NON-EXISTANT TACS VARIABLE, SO THE REQUEST WILL BE DISREGARDED.

41\.

42. TEMPORARY ERROR STOP. LIST 17 SIZE (NUMBER OF DYNAMIC S.M. BUSSES) AS CONTROLLED BY THE USER DOES NOT EQUAL THE INTERNAL FIXED DIMENSION FOR THE S.M. CODE. THESE VALUES ARE ____ AND ____, RESPECTIVELY.

43. NOTE ---- COLUMN NUMBER ____ OF THE LAST-READ DATA CARD IS NON-BLANK, THEREBY REPRESENTING A REQUEST FOR OUTPUT OF THE ____ OF MASS NUMBER ____ OF THIS SYNCHRONOUS MACHINE (S.M.). BUT THIS S.M. HAS A SHAFT SYSTEM WHICH IS COMPOSED OF ONLY ____ MASSES. THIS OUTPUT REQUEST WILL BE IGNORED BY THE EMTP.

44 WARNING. BLOCK '____' HAS ITS LIMITER OPERATING DURING THE TACS DC STEADY-STATE SOLUTION. DOUBLE-CHECK THE PROGRAM OUTPUT FOR T = 0.0 FOR ANY MISUNDERSTANDING BETWEEN THE PROGRAM AND THE USER.

45. NOTE ---- COLUMN NUMBER ☐ OF THE LAST-READ DATA CARD IS PUNCHED WITH THE DECIMAL DIGIT '0' . BUT THIS IS NOT A RECOGNIZABLE REQUEST FOR AN OUTPUT VARIABLE. THE EMTP WILL IGNORE THIS REQUEST, PRETENDING THAT THE COLUMN IN QUESTION IS BLANK ON THIS DYNAMIC S.M. OUTPUT-SPECIFICATION CARD.

46. COMPLICATION. ---- THE DYNAMIC SYNCHRONOUS MACHINE (S.M.) NOW BEING INPUTTED, TAKEN TOGETHER WITH ALL PRECEDING MACHINES, HAS OVERFLOWED THE AVAILABLE WORKING STORAGE FOR S.M. OUTPUT QUANTITIES OF THE TIME-STEP-LOOP PRINTOUT. THE PROGRAM LIMIT (AS PRESENTLY DIMENSIONED) IS ☐ S.M. OUTPUT QUANTITIES. IF REQUESTS FOR THE PRESENT MACHINE WERE TO BE HONORED, A TOTAL OF ☐ CELLS (INCLUDING ☐ FOR THE PRESENT MACHINE) WOULD BE REQUIRED. AT THIS POINT, THE EMTP LOGIC WILL IGNORE ALL OUTPUT REQUESTS FOR THE PRESENT MACHINE, AND WILL CONTINUE WITH THE READING OF INPUT DATA CARDS.

47. NOTE. ---- THE LAST-READ DATA CARD BELONGS TO A DYNAMIC SYNCHRONOUS MACHINE, FOR WHICH THE PARAMETERS ARE TO BE MATHEMATICALLY FITTED WITHIN MODULE 'SMPFIT' OF OVERLAY NUMBER 5. THE USER REQUESTED THIS PROCEDURE BY MEANS OF THE 'PARAMETER FITTING' CARD WHICH ACCOMPANIED THE DATA CARDS FOR THIS MACHINE. BUT THE NEWTON ITERATION OF THIS FITTING PROCESS HAS NOT SUCCESSFULLY CONVERGED TO TOLERANCE 'EPSILN' = ☐ WITHIN THE ITERATION LIMIT OF 'NIAMAX' = ☐. THE LAST ITERATION WAS NUMBER ☐.

ACTUALLY, THE EMTP LOGIC HAS DETERMINED THAT THE ITERATION IS DIVERGING (BLOWING UP), AND SHOULD NOW BE STOPPED IN ORDER TO AVOID NUMERICAL OVERFLOW. ONE OR MORE COMPONENTS OF THE NEWTON CORRECTION VECTOR FOR THE LAST ITERATION HAVE EXCEEDED THE DIVERGENCE TOLERANCE 'EPSDIV' = ☐ .

WELL, HAVING FAILED TO MATHEMATICALLY FIT THE MACHINE PARAMETERS, THE EMTP LOGIC WILL NOW RECOVER, AND WILL SIMPLY IGNORE THE 'PARAMETER FITTING' CARD. INPUT DATA PARAMETERS OF THIS GENERATOR WILL BE USED AS THEY WERE READ FROM THE INPUT DATA CARDS, WITHOUT ALTERATION.

48. NOTE ----- THIS DATA CASE EMPLOYS THE REFERENCE-BRANCH FEATURE FOR LINEAR BRANCH CARDS, IN A WAY WHICH IS TRICKY. IF NOT SO INTENDED BY THE USER, THIS IS POTENTIALLY A VERY HAZARDOUS SITUATION, CAPABLE OF RESULTING IN ERRONEOUS SIMULATIONS. FOR THIS REASON, THE FOLLOWING INFORMATIVE DIAGNOSTIC INFORMATION IS BEING PROVIDED. IN ONE OR MORE INSTANCES, THE EMTP HAS OBSERVED THAT USAGE OF THE ORDERED PAIR OF REFERENCE NAMES (READ FROM DATA FIELDS 'BUS3' AND 'BUS4' , COLUMNS 15-26) IS NOT UNIQUE. WERE IT NOT FOR THE RULE THAT THE FIRST SUCH QUALIFIED COMPONENT FOUND (IN ORDER OF DATA INPUT) IS ARBITRARILY TAKEN AS THE REFERENCE COMPONENT, THERE WOULD BE AMBIGUITY. SUCH SITUATIONS ARE LISTED BELOW, WHICH SHOULD BE CAREFULLY CHECKED BY THE USER TO VERIFY THAT THE CORRECT REFERENCES ARE INDEED BEING USED BY THE EMTP.

☐. ROW ☐ OF TABLE CONNECTS BUS '☐' WITH BUS '☐' . BEGINNING R , L , C VALUES USED = ☐ ☐ ☐ . THIS IS REJECTED BECAUSE IT WAS NOT THE FIRST FOUND.

⁝ Etc. ⁝

☐. THE PRECEDING ELEMENTS WERE ALL REJECTED BECAUSE THEY WERE PRECEDED BY THE ENTRY OF ROW ☐ OF THE TABLE, WHICH CONNECTS THE SAME ORDERED PAIR OF BUSSES. BEGINNING R , L , C VALUES OF THIS CHOSEN REFERENCE BRANCH = ☐ ☐ ☐ . IT IS THIS LATTER ENTRY WHICH IS USED AS REFERENCE BY THE BRANCH OF ROW ☐, WHICH CONNECTS BUS '☐' WITH BUS '☐' (AND WHICH IS THE FIRST OF ONE OR MORE USAGES OF THE REFERENCE BRANCH IN QUESTION).

49. THE NUMBER OF ENERGIZATIONS FOR THIS STATISTICS RUN IS 1. VARIANCE AND STANDARD DEVIATION CANNOT BE COMPUTED.

50.

```
****************************************************************************************************
WARNING.  ----  ONLY [    ] CELLS ARE AVAILABLE FOR WORKING STORAGE THAT IS REQUIRED BY THE CODE WHICH PRINTS
                OUT STEADY-STATE ARMATURE CURRENTS FOR DYNAMIC SYNCHRONOUS MACHINE COMPONENTS.   EIGHT CELLS ARE USED
                FOR EACH SINGLE-MACHINE COMPONENT, AND TWELVE FOR EACH DUAL.   RESULTS WHICH WOULD BE STORED IN CELLS
                NUMBERED GREATER THAN [    ] WILL GENERALLY BE ERRONEOUS.   HENCE BEWARE, IN READING THE INITIAL-
                CONDITION ARMATURE-CURRENT PRINTOUT WHICH MAY FOLLOW, AS WELL AS S.M. TIME-STEP OUTPUT AT  T=0 .
****************************************************************************************************
```

51.

```
WARNING ---- NODE RENUMBERING OF THE TRANSIENTS NETWORK HAS BROKEN DOWN, PRESUMABLY DUE TO TABLE OVERFLOW
(I.E., THE NETWORK IS TOO BIG AND/OR TOO DENSE FOR THE PRESENT EMTP DIMENSIONING).   THE NEXT TIME THAT THE USER
REDIMENSIONS THE EMTP, HE IS ADVISED TO INCREASE THE SIZE OF LIST NUMBER  5  AND/OR  8 .   BOTH OF THESE LISTS
CONTRIBUTE FULLY (100 PER CENT) TO DEPENDENT LIST NUMBER  99 ,   WHICH IS WHAT HAS ACTUALLY OVERFLOWED AT THIS POINT.
[    ] NODES OUT OF TOTAL OF [    ] WERE RENUMBERED BEFORE BREAKDOWN IN THE RENUMBERING OVERLAY.
HAD WE MADE IT TO  [    ]  NODES, THE OPERATION WOULD HAVE TERMINATED NORMALLY (SINCE THE REMAINING ONES
ARE ALWAYS FORCED LAST WITHOUT REGARD TO SPARSITY CONSIDERATIONS).

ANYWAY, THE EMTP WILL TRY TO CONTINUE WITH EXECUTION OF THIS DATA CASE, AS BEST IT CAN.   NODES WHICH WERE
NOT RENUMBERED BEFORE THE OVERFLOW LIMIT WAS REACHED WILL NOW SIMPLY BE RENUMBERED IN THEIR ORIGINAL RELATIVE
ORDER, WITHOUT REGARD TO SPARSITY CONSIDERATIONS.   RECALL THAT THE ORIGINAL NODE ORDER COMES FROM THE ORDER OF DATA
INPUT (THE ORDER IN WHICH NODE NAMES ARE ENCOUNTERED, AS THE EMTP DATA CARDS ARE READ).
THE FINAL RENUMBERING MAP   (NORDER(I), I=1, NTOT)   WILL THEN APPEAR AS FOLLOWS ....
   1     2     3     4     5     6     7     8     9    10    11    12    13    14    15    16    17    18    19    20
  21    22    23    24    25    26    27    28    29    30    31    32    33    34
THE  K-TH  SUCH ENTRY GIVES THE ROW (AND COLUMN) POSITION OF OLD VARIABLE  K  IN THE REORDERED MATRIX.
```

52.

```
WARNING.  TACS VARIABLE '[    ]' IS ALLOWED TO OPERATE OUTSIDE ITS LIMITS DURING THE STEADY-STATE SOLUTION.
```

53.

```
NOTICE ----- OVERVOLTAGE TABULATION FOR THIS VOLTAGE VARIABLE CAN NOT CONTINUE, DUE TO INSUFFICIENT WORKING
             SPACE.   STATISTICS MISCELLANEOUS DATA PARAMETER  'XMAXMX'  HAS BEEN EXCEEDED BY THE PEAK PER UNIT
             OVERVOLTAGE (ACTUALLY, EXCEEDED BY  3.2  TIMES OR MORE).
```

54.

```
***** WARNING WARNING *****
POSSIBLE LOSS OF SIGNIFICANCE IN ELIMINATION STEP [    ]  WITHIN  'DGELG'  WHICH IS CALLED BY  'SOLVSM' .
```

55.

```
ONE OR MORE NONEXISTENT NODE NAMES IN VOLTAGE      DIFFERENCE  '[    ]'  TO  '[    ]' .   THIS REQUEST IGNORED.
```

56.

```
REQUEST FOR VOLTAGE OUTPUT OF NONEXISTENT NODE '[    ]' WILL BE IGNORED.
```

57.

```
COMMENT.  ---- ONE OR MORE OF THE FOUR S.M. TIME CONSTANTS JUST INPUTTED IS LESS THAN TEN TIMES THE
               TIME-STEP SIZE  'DELTAT' .    THE VALUES INVOLVED ARE AS FOLLOWS ....
                       TDOP          TQOP          TDOPP          TQOPP        10*DELTAT
                     [      ]      [      ]      [      ]      [      ]      [      ]
```

58.

```
WARNING.  ----  FREQUENCY SENSOR  '[    ]'  HAS ZERO CROSSING AT  [        ]  SEC.   BUT NEW FREQUENCY
                OF [        ]  HZ   DIFFERS BY OVER FIFTY PERCENT FROM THE OLD FREQUENCY OF [        ]  HZ .   REJECT IT.
```

46h

59.
```
WARNING.  ----  VALUE OF DELAY EXCEEDED MAX. DELAY VALUE OF
                FOR '      '  AT TIME =
                THIS MESSAGE WILL NOT BE REPEATED.
```

60.
```
WARNING.  ----  THE PULSE FREQUENCY AT THE PULSE TRANSPORT DELAY  '    '  IS TOO FAST FOR THE PRESENT
                DELAY OF            SEC   AT SIMULATION TIME              SEC.
```

61.
```
WARNING.  ----  VALUE OF DELAY BECAME NEGATIVE FOR '        ' AT TIME =
                BUT LOWER LIMIT VALUE =  0.0  .
                THIS MESSAGE WILL NOT BE REPEATED.
```

Message 1 : XREF (F6.2) , XOPT (E13.4)

Because any given country will generally have only one synchronous power frequency (60 Hz for the USA and Canada), nonzero miscellaneous data parameter "XOPT" will typically always equal this power frequency. Message number 1 simply reminds the user of any other nonzero usage of floating-point miscellaneous data parameter "XOPT" . The reference value "XREF" is assigned within system-dependent module "SYSDEP" of overlay 1 , and hence this value may vary from translation (of the UTPF; recall that the EMTP is produced by machine translation) to translation. In particular, our European friends will generally want to set this reference value to 50. (for 50 Hz).

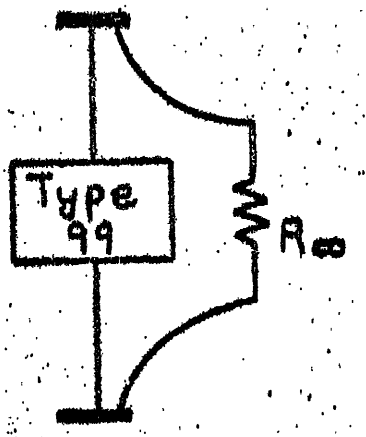
Message 2 : COREF (F6.2) , COPT (E13.4)

This explanation is identical to that for Message 1, only here the EMTP is concerned with miscellaneous data parameter "COPT" rather than "XOPT" .

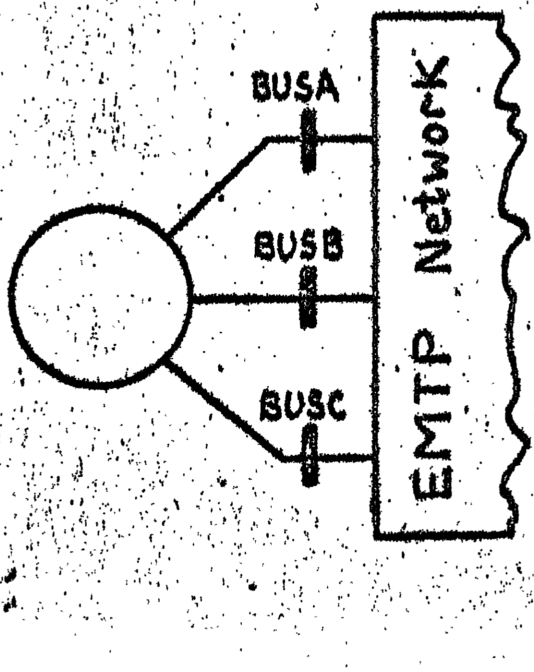
Message 3 : BUS1 (A6) , BUS2 (A6) , R (E6.1)

There are actually two distinct messages in this class, one for type-99 pseudo-nonlinear resistance elements, and the other for dynamic synchronous machine components. They are grouped together here only because both involve the internal addition of a very high impedance resistor, for purposes of connectivity.

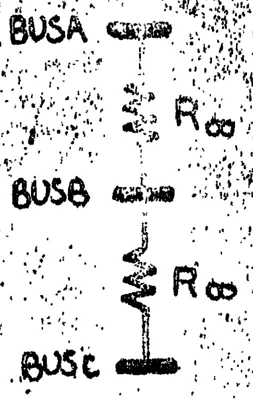
If the user has not paralleled each type-99 pseudo-nonlinear resistance element by a lumped linear element, then the EMTP will internally connect very high impedance resistors across such elements. Such a branch should not significantly affect the solution, of course. The user is informed of such an automatic addition by means of Message 3 printout, where the 80-column card image listing and interpretation are provided almost as though the user had inputed the branch himself. The card-image listing will show the terminal node names "BUS1" and "BUS2" of the type-99 nonlinear element (printed in cols. 3-14); the resistance value "R" will appear in columns 27-32.



The second, related usage is for dynamic synchronous machines. See the sketch at the right, where the three armature terminal busses for phases "a" , "b" , and "c" have been given names "BUSA" , "BUSB" , and "BUSC" , respectively. Now if the three armature phases are not appropriately coupled to each other electrically , through the network by means of branches which physically terminate on "BUSA" , "BUSB" , and "BUSC" , then the EMTP will automatically add high-impedance resistive branches to provide such coupling. Such branches should not significantly affect the solution, of course. Two internally-



defined resistors are involved, connecting "BUSA" with "BUSB" and "BUSB" with "BUSC" ; each has an ohmic value of .01/FLZERO , where "FLZERO" is the EMTP variable of /BLANK/ which gives a measure of the floating-point precision limit of the computer being used. "FLZERO" is assigned within system-dependent module "SYSDEP" of overlay 1 , so is a function of the translation being used. For 60-bit CDC or 64-bit (8-byte) IBM translations, a value of 1.E-12 is typical. Message 3 then provides two lines of printout for a given synchronous machine to which this inter-phase resistive coupling is being added. These simulate the 80-column card-image listing and interpretation which would have existed had the user inputed such resistive branches himself. The reader should note carefully the original phraseology about phases being "appropriately coupled". In particular, a 3-or-more-phase distributed line or Pi-circuit will satisfy the coupling requirement if connected to the machine terminals, provided the phase are ordered with conductors 1 , 2 , and 3 connected to machine terminal busses "BUSA" , "BUSB" , and "BUSC" , respectively.



It should be mentioned that the reference branch procedure is used for these internally-defined high-resistance elements. Only the first one will show "R" as being punched in columns 27-32 . All later branches will hav columns 27-32 left blank, but with "BUS3" and "BUS4" of columns 15-26 referencing the first such branch. A small amount of List 3 storage space is in this way saved by the EMTP.

Message 4 : N1 (I3) , MODOUT (I3)

This message is simply a reminder that the EMTP output vector may not be quite what labeling would imply, if the user has requested the special "MODE VOLTAGE OUTPUT" option which is described in Section 1.0f . Recall that Karrenbauer mode voltages at both ends of one transmission line are available for output purposes, by means of this devious option. The user inputs variable "MODOUT" (I8 information read from columns 33-40), and "N1" is always twice this value. Message 4 will always be printed for a data case which uses the "MODE VOLTAGE OUTPUT" option, immediately before the output-variable headings for the time-step loop.

Message 5 : (NORDER(I), I=1, NTOT) (20I6)

Immediately preceding the three lines of diagnostic text of Message 5 will be found printout of (NORDER(I), I=1, NTOT) , which is the renumbering map from original numbers (assigned according to order of input) to transient node numbers (internal node numbering, as used for the network solution within the time-step loop). Ground is always given number one, and must be preserved this way by renumbering. Yet if the renumbering routine itself (module "OVER7" .) does not do this, the following EMTP code must manually make the adjustment as per the printed message. The user should not he bothered by this message, which really is just a public notice of some internal adjustments which are being made. This diagnostic seems to generally occur in practice only for very small test problems, it has been observed.

Message 6

If nonlinear, time-varying, or pseudo-nonlinear elements are present in the user's data case, he is simply reminded that the phasor (sinusoidal steady-state) solution for initial conditions requires a linear representation. Specifically, resistance elements are all assumed to be open circuits (i.e., they are "ignored"), while inductance elements are represented by linear inductances.

Message 7

The typical data case will generally involve one or more type-14 source elements which are present as part of the phasor (sinusoidal steady-state) solution for initial conditions. But if no such sources are present, there is no need to perform a phasor solution, since it is known to be identically zero. It is of this latter situation that the user is reminded by Message 7.

Message 8

As per Section 1.-b , multiple voltage sources on a single node are all interpreted as being connected in series. Message 8 is simply a reminder to the user of all such situations, for type-14 sources which are present during the phasor solution for initial conditions.

Message 9

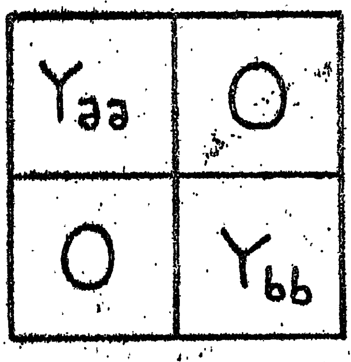
If a current source and a voltage source are paralleled, then the current source has no effect on the network solution. This is the meaning of having two such sources connected to the same node (the A6 name of which is read from columns 3-8 of the source card). At least for the phasor (sinusoidal steady-state) solution for initial conditions, to which Message 9 applies, such extraneousness is pointed out to the user.

Message 10

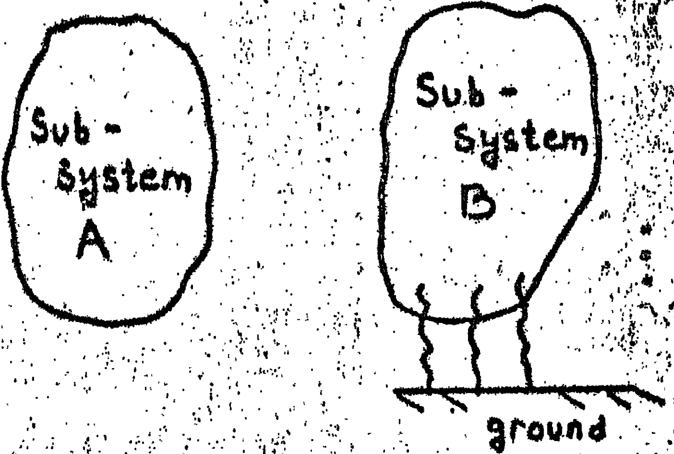
The phasor (sinusoidal steady-state) solution for initial conditions is performed for only a single frequency, namely that of the first type-14 source (in order of data input) which is present in the sinusoidal steady state. That is, the first source having field "TSTART" of columns 61-70 punched with a negative value. Any other type-14 source having "TSTART" punched negative will also be accepted at this same frequency, provided the requested frequency (columns 21-30) does not differ by over on percent from the original (first) frequency. Deviations of over one percent will exclude such a source from the phasor solution, and produce the Message 10 text. Such an exclusion is equivalent to having "TSTART" punched non-negative for that source. The user should always pay attention to such a message, for if he did not plan on such exclusions, he will be getting a solution which is probably not at all what he expected.

Message 11 : BUS1 (A6) , D1 (E12.3) , D2 (E12.3) , D3 (E12.3)

This warning message is printed out when the elimination process on the phasor (sinusoidal steady-state) network equation set $[Y]\bar{V} = \bar{I}$ has been temporarily suspended due to the occurrence of a near-zero diagonal element just before that element is to be reciprocated. Of course all computers have limited precision for their floating-point representation, so it is impossible to say whether in theory an exact zero (as opposed to just a very small) diagonal element has been encountered.

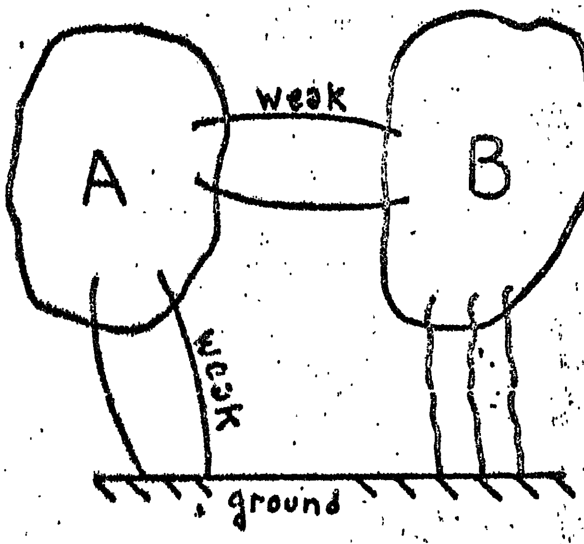


If the phasor network consists of two disconnected subnetworks as sketched at the right, the associated complex nodal admittance matrix $[Y]$ is block diagonal, as sketched above. Of course ground is the reference node for the equations, which for purposes of this explanation may be assumed to be in subsystem B without any loss of generality. Then subsystem A has no path to ground, nor to any non-ground node of subsystem B . Submatrix $[Y_{aa}]$ is then singular (uninvertible), which will show up during triangularization as the elimination on the last row of $[Y_{aa}]$ is being completed; after elimination to the left of the diagonal, a zero diagonal element will be observed ——— identically zero in theory, a "near-zero" floating-point number in practice.



The tolerance which is used for near-zero checking of diagonal elements just before reciprocation is floating-point miscellaneous data parameter "TOLMAT" . While the user can define (input) whatever positive value he wants for this variable, it is common to use the EMTP default value. For blank or zero field "TOLMAT" on the user's floating-point miscellaneous data card, the installation dependent default value is assigned (the numerical value of which is set up in system dependent module "SYSDEP" of overlay 1. The fourth printout variable of Message 11 is D3 = TOLMAT**2 .

The "original diagonal value" which is mentioned by the message text is the value of the diagonal element of the matrix for the row which is causing trouble, before the elimination has begun. The "questionable value" which is mentioned by the message text is the value of this same diagonal element just before the reciprocation which is not being allowed. Note that "magnitudes squared" are used for all quantities. This is because the matrix [Y] is complex (has both real and imaginary parts), and yet all the user wants is a single real number which gives an indication of how small the diagonal element in question is. The magnitude or modulus of the numbers would be the natural choice, though the squares of these have been used for convenience.



If the subnetwork in question really is disconnected from the rest of the system and ground, then the stated EMTP identification and associated corrective action (setting subnetwork voltages to zero) was of course correct. In this case, the user should be happy.

On the other hand, if ties do exist from subsystem A to subsystem B (see sketch), then these ties are just too [illegible] has been fooled. In this [illegible] either the network parameter values or "TOLMAT" , or both, should be modified, since the solution with zero voltages for subsystem A nodes will generally be grossly incorrect. The resulting transient simulation may well have a substantial extraneous discontinuity or shock at time zero, because of the erroneous initial-condition voltages, note. For this reason, the user should always pay attention to Message 11, and verify that it only appears for cases where the subsequent zero-voltage solution is acceptable and correct.

One special problem concerning Message 11 has to do with phasor solutions at frequencies which differ drastically from the synchronous power frequency. For example, dc initial conditions representing trapped charge on an unenergized line may commonly be generated by a phasor solution using frequency 0.001 Hz . But in such a case, the impedance of small "isolation" reactances become extremely small; and the impedance of capacitors becomes very large. What might well have been good strong coupling at 60 Hz can become very weak coupling at such a drastically altered frequency, then. For such usage, small isolation resistors may then be preferable to isolation reactors, since the impedance of a resistor is of course frequency invariant.

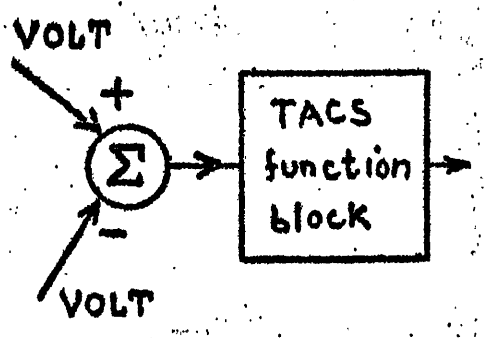
Message 12

In case program execution is to be stopped after the steady-state phasor solution is complete (which is the case if floating-point miscellaneous data parameter "TMAX" is punched non-positive), the steady-state phasor solution for transients variables is always provided. This is in addition to, and subsequent to, the possible printout of the complete steady-state solution which is controlled by integer miscellaneous data parameter "KSSOUT" . Selective node voltage output requests are read as per the description of Section 1.8a . Should one or more of these A6 node names be illegal (i.e., non-existent in the user's previously-defined network), then the text of Message 12 will result. This is usually the result of a spelling error, which includes the proper positioning of blank characters in the field of width six.

Message 13

This message is clearly equivalent to Message 7, only is located in a different overlay. It's a little embarrassing, running across such duplication.

Message 14 : BUS1 (A6) , BUS2(A6)



TACS function blocks (see Section 8.5.1) all have summing junctions on the input end. As many as five A6 names of TACS variables can be specified, as inputs to the function block under consideration. Sometimes such an input name may legitimately be repeated. For example, if 2 * VOLT is wanted as an input, the user could avoid a multiplication by two if he would input "VOLT" twice (VOLT + VOLT) . Here the signs of the repeated input variable are the same —— both positive. But what if the user has opposite signs, producing exact cancellation (e.g., VOLT - VOLT) ? It is not clear how such a situation could have any useful engineering significance, but it is allowed by the EMTP. In fact, this cancellation is produced at data-input time, rather than numerically as the simulation progresses. The result is just as though the user had never punched the inputs in question.

Message 15

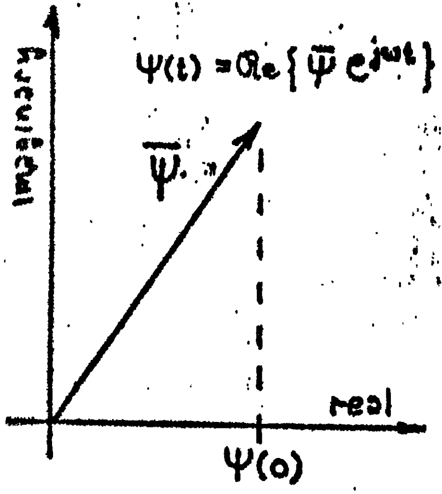
The initial-flux message (one of 1st two lines of printout) will be outputed by the EMTP for every inductance element of the data case which is other than perfectly linear. Included, then, are:

1. Type-98 pseudo-nonlinear reactors of Section 1.29 . Recall that the saturable transformer component of Section 1.25 has a built-in type-98 element for the magnetizing branch, provided the characteristic is truly nonlinear (two or more points used to define it).

2. Type-93 true nonlinear inductance element of Section 1.33 .

3. Type-93 switch (switched-inductance) element of Section 1.52 .

The last of the 3 printed lines is only outputed if th flux in question is "out of bounds". It is important to realize what such message means, and also what it does not mean.



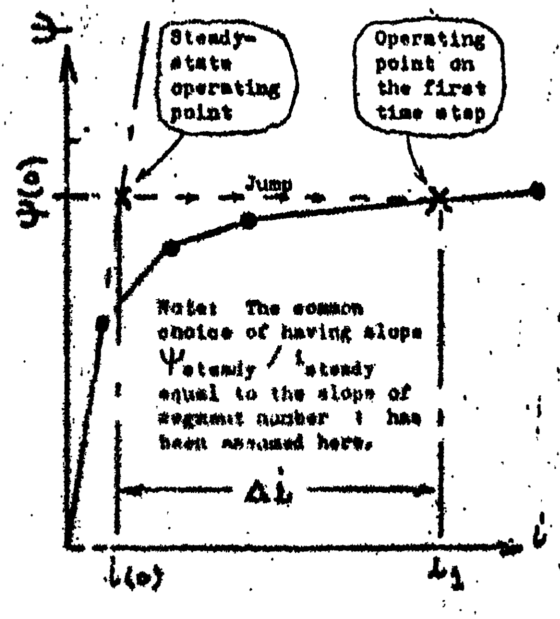
First, what Message 15 does not mean. Absence of the message does not mean that sinusoidal steady-state peak phasor flux is within the bound which is being checked. It is only the flux value at time zero —— which is to be used as an initial condition for the subsequent transient simulation —— that is checked. This is the projection of the complex phasor $\bar{\Psi}$ on the real axis. It is possible for $|\bar{\Psi}|$ to be way out of bounds, and yet $\Psi(0)$ might be small or even zero. Absence of such a warning message thus does not imply that the true steady-state, periodic solution is sinusoidal; it may in fact be highly nonsinusoidal.

Second, there is the limit value which $\Psi(0)$ is checked against. For the true nonlinear and the pseudo-nonlinear elements, the assumed limit is Ψ_{steady}, as read from columns 33-38 of the first card defining the component in question. For switched-inductance elements, it is the breakpoint flux Ψ_s which is used, as read from columns 45-54 of the switch card.

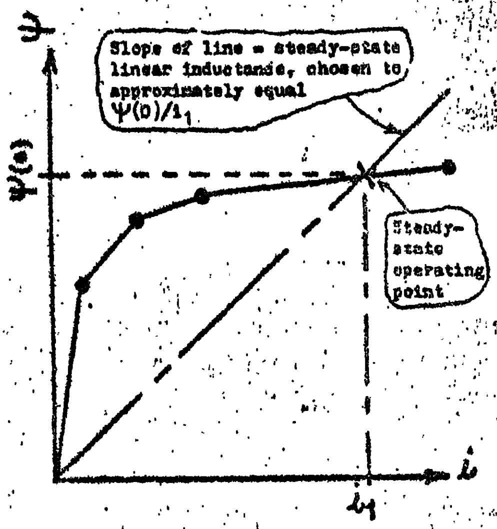
Finally, there is the potential numerical complication which may result from initial flux being "outside the linear region".

1. For the type-93 true nonlinear inductance element, on the first time step operation will transfer to the nonlinear characteristic (see sketch). This will generally be a nearly horizontal jump (constant flux trajectory), which implies a sudden change Δi in the current. The result may well be an extraneous shock to the system, and a spurious transient. For example, if the current jump Δi is supplied through a linear inductor L in the time step of size Δt, a spurious voltage change on the order of $\Delta v = L \Delta i / \Delta t$ will appear across that element. For small time step Δt, this may be astronomical.

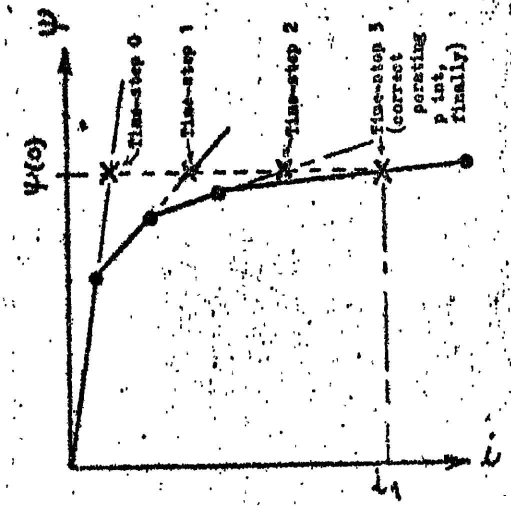
   As a remedy to the just-stated difficulty, the user is free to pick i_{steady} and Ψ_{steady} so that the steady-state line passes through (or almost through)


Ψ
Steady-state operating point
Operating point on the first time step
$\Psi(0)$
Jump
Note: The common choice of having slope $\Psi_{steady} / i_{steady}$ equal to the slope of segment number 1 has been assumed here.
Δi
i
$i(0)$
i_1

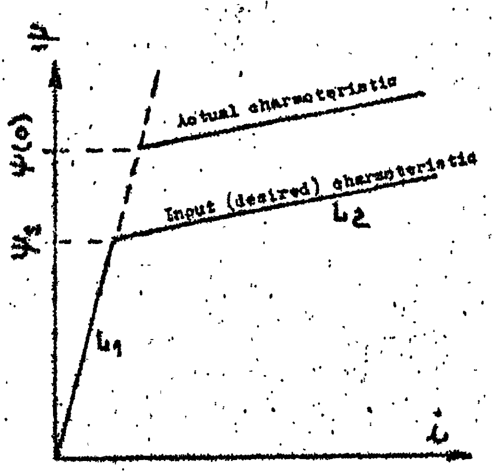
the transient operating point. This is shown in the second sketch, below the original. If done careful, the shock at time zero can be effectively eliminated, generally.


ψ
Slope of line = steady-state linear inductance, chosen to approximately equal ψ(0)/i₁
ψ(0)
Steady-state operating point
i
i₁

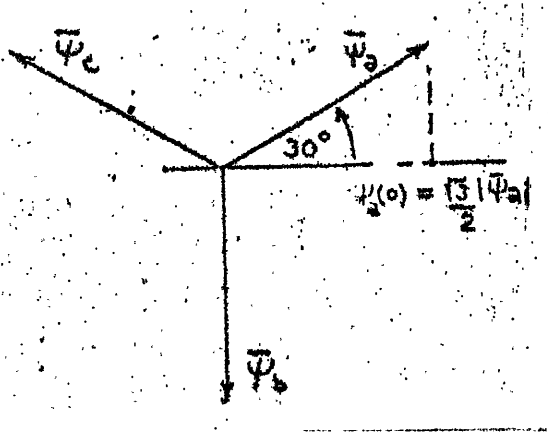
2. For the type-98 pseudo-nonlinear inductance element, the preceding general idea of a current jump Δi at time zero is applicable. However, present type-98 element logic allows only one segment change per time step, with operation always beginning on the first segment, at time zero. Hence on the first time step operation might switch to segment number 2, on the second step to segment number 3, etc., as shown at the right. It thus may require more than one time step for operation to move to the nonlinear characteristic.



3. The switched-inductance element will simply switch from the linear slope L_1 to the saturated slope L_2 on the first time step —— an operation which is well behaved numerically. Yet the user should note that operation will not be on the characteristic which he thought he was inputing! Rather, it will be on a line parallel to the inputed saturation segment, higher in the ψ-i plane (see sketch), which intersects the extension of the unsaturated segment at flux value $\psi(0)$. This is because the EMTP representation consists of paralleled linear inductors, with a switch in series with one of them (see Section 1.52).



As a general remedy for the preceding complication, the user can often advantageously rotate source angles, for a balanced 3-phase system. This does not affect the problem physically, of course, since one is thereby simply redefining the time instant which one chooses to call zero. The optimal situation is to have fluxes (currents) situated at 30°, 150°, and 270° in the complex plane (phasor diagram), so that all three initial values are limited to $.866 = \sqrt{3}/2$ times the peak value. This gains 13.3% compared with the worst choice, which is frequently enough to eliminate Message 15 texts.



Message 16

This message text is purely informative, and is in no way a complication which should worry the user, provided data parameters for the line in question are correct. If the user is keeping track of the number of memory locations required to store the past history (List 8 of Section 0.6), he is simply reminded that no cells are required for the particular distributed line which is listed —— because it has zero initial conditions (there was no phasor solution) and all modal travel times for the line are less than the terminal study time "TMAX" (floating-point miscellaneous data parameter). The idea here is that the EMTP is not going to store past history if the simulation will not be continued long enough for any of it ever to be used.

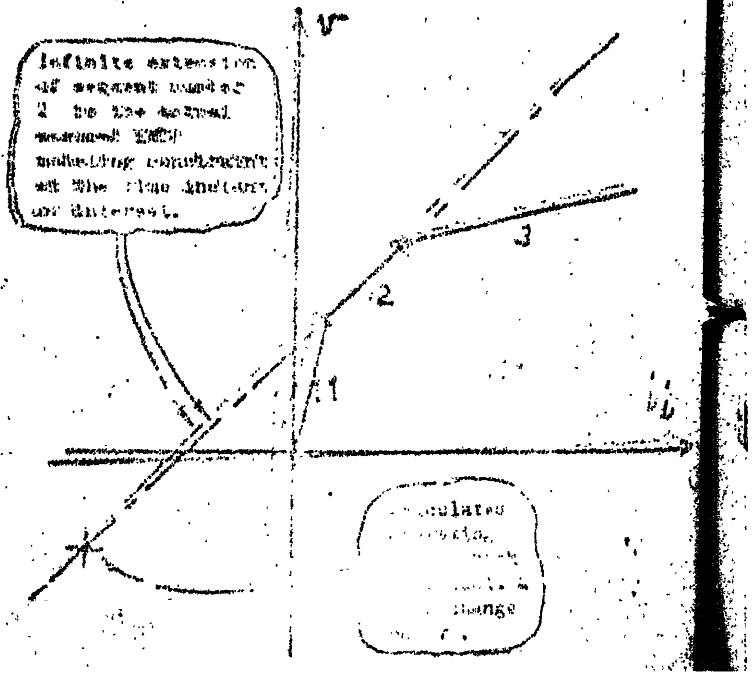
Message 17 : N1 (I6) , NENERG (I6) ; SIGMAX (F8.4)

This message can appear only during execution of the special test procedure for the EMTP random-number generator. Recall that if integer miscellaneous data parameter "NENERG" (see Section 1.0h) is positive, and if "ISW" of the following "STATISTICS" miscellaneous data card has value 4444 , then such a special test will occur. Switch closing times for the EMTP data case are generated, but no subsequent simulations are actually run. Instead, such switch closing times are simply tabulated for user scrutiny. The user specifies "SIGMAX" as the number of standard deviations on each side of the mean over which this tabulation is to be produced. If this is 3.0 or 4.0 , most likely none of the sample switch closing times will fall outside the range of the tabulation, and no such Message 17 text will be seen. But should N1 > 0 sample switch closing times (out of the "NENERG" which were requested by the user) fall outside the tabulated range, this Message 17 text will be outputted immediately after the closing-time tabulation.

Message 18

If the user ever gets this message, simulation results must be viewed with extreme skepticism; he should review the transient characteristics of the problem being solved, to understand why the modeling being used is deficient. Modeling should then be altered, and the simulation re-run, since in most cases the present results (producing Message 18) are erroneous in some way —— perhaps totally.

Message 18 is associated with pseudo-nonlinear element trouble. Specifically, operation was on some segment other than that passing through the origin, when a sign change of the ordinate (v or ψ) has been found. See the sketch at the right, where operation on segment number 2 has been assumed for purposes of illustration. While operating on the infinite extension to segment number 2, a solution with negative ordinate value has been calculated. Clearly we are not moving slowly up and down the characteristic, then, which was one of the underlying assumptions behind successful pseudo-nonlinear element usage. Once operation


v
Infinite extension of segment number 2 to the actual assumed EMTP modeling constraint at the time instant of interest.
3
2
1
i
[illegible]lated
[illegible]hange

ceases to track the characteristic, the simulation becomes invalid, of course, from that point on.

It is important for the user to realize that the Message 18 text is sufficient to show erroneous pseudo-nonlinear element usage, but that its appearance is not necessary for such erroneous operation. Quite erratic, jerky, unacceptable tracking of the characteristic will go without any warning message, should such occur without a sign change of the ordinate variable (v or ψ).

Type-98 elements should always be well behaved, with the possible exception of the discontinuity at time zero. This is because the ordinate variable ψ is the integral of another network solution variable, $\psi = \int v\,dt$. Changes in ψ from one time step to another can be made arbitrarily small, then, by decreasing the time-step size "DELTAT" (floating-point miscellaneous data parameter). Appearance of Message 18 for a Type-98 element is usually an indication that the simulation is diverging numerically (i.e., blowing up). In this case, voltage magnitudes become arbitrarily large, and flux changes over one time step are no longer small.

It is type-99 elements which can "get into trouble", if not connected across a network element which maintains continuity of voltage either directly or indirectly. Connection across a capacitor should make them perfectly well behaved, since capacitor voltage is inherently continuous. At the other extreme, connection across an inductor can frequently cause trouble, since such voltage is capable of drastically changing from one time step to another. The EMTP memorandum dated August 26, 1974 (Reference 8) documents such difficulty.

Message 19

Identical in meaning to Message 12, only this particular output is for cases which do involve transients simulation; here the end-time of the study, floating-point miscellaneous data parameter "TMAX" , is positive.

Message 20

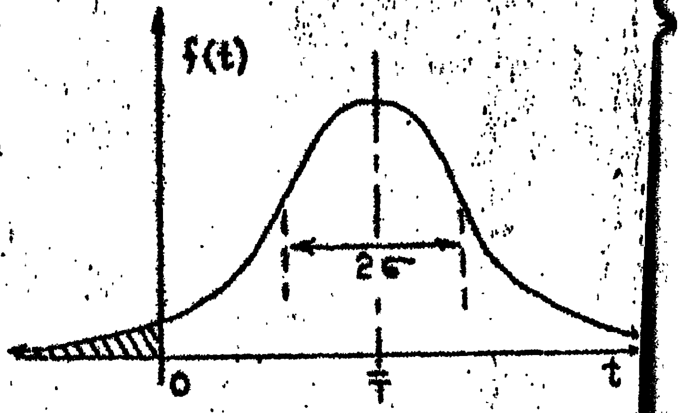
The TACS dc steady-state initialization for t = 0.0 is entered if at least one TACS source of type 01, 92, or 93 is defined as active with TSTART < 0.0 . Initial conditions are calculated for most s-blocks (see details in Section 8.4) and for all order-zero blocks. Should the user provide a user-defined initial condition for a variable that is already considered in the above calculation, this user-defined initial condition will be ignored, and the calculated dc initial condition will prevail. Note that the TACS ac steady-state initialization is a separate procedure, the results of which are superimposed to the dc initial conditions, whether the latter are TACS-calculated or user-defined.

Message 21

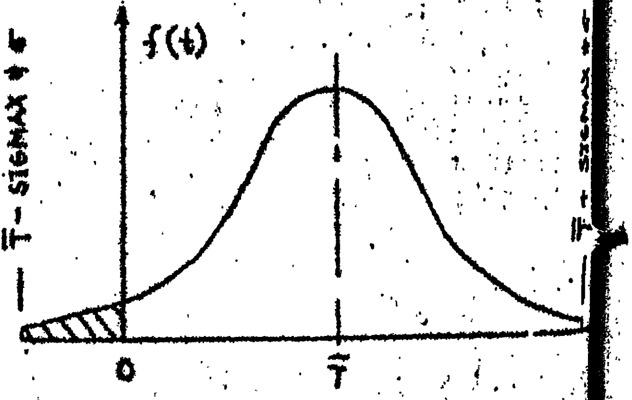
Integer miscellaneous data parameter "IPUN" provides for the option of punching terminal conditions of the study, if so desired. But this only works for data cases which have no distributed lines. If the user tries to exercise this punch option for a data case having distributed parameter lines, the punching will be aborted with the text of Message 21.

Message 22

When using a Gaussian distribution for random switch closing times of a statistical overvoltage study, there is always a finite probability of generating negative closing times —— irregardless of the prescribed mean closing time $\bar{T}$ and standard deviation σ. This is shown in the sketch of the density function at the right, where the shaded area under the left tail gives the probability of a negative, illegal switch closing time. This is for each switch, for each energization (each time we roll the dice). Since the simulation begins at time zero, the EMTP has no way of representing such negative closing times; and this is why they are called "illegal". The best the EMTP can do is close as soon as possible, namely at time zero.



Future versions of the EMTP will have the option of cutting off the tails of a Gaussian density function f(t) at some user-specified number "SIGMAX" of standard deviations from the mean. Yet if $\bar{T}$ - SIGMAX * σ is negative, there will still remain the possibility (probability) of negative switch closing times.



The text of Message 22 is simply informative, to remind the user that the internally-generated random numbers have been distorted so as to fit into the underlying EMTP framework. If a significant fraction of the closing times show up as having been converted to zero, the user is advised to appropriately increase the associated mean closing times T , thereby eliminating the problem. Recall that time is relative anyway, with the instant of time which is called zero an arbitrary choice of the user.

Message 23

Section 1.10-B-7 shows how the user can redefine the spacing between Calcomp plots by means of a special request card which bears the key word "MARGIN" in columns 25-30. The new inter-plot separation is the single-digit integer variable read from column 4 (field "KSEP"), which is in inches. To be legal, this must be greater than or equal to two inches. If zero or unity is punched in column 4, such a request is ignored, and the text of Message 23 is generated; the EMTP continues to use whatever separation was in effect at the time of the illegal request.

Message 24

Section 1.10-B-8 shows how the user can redefine the smoothing tolerance which is used for Calcomp plotting, by means of a special request card which bears the key word "SMOOTH" in columns 25-30. While any positive value for the new tolerance "EPS" (read from columns 16-20) is permitted, large values will lead to rather jagged looking plots. The text of Message 24 is outputed to warn the user, should he use a tolerance of 0.1 inches or more.

Message 25

Section 1.10-B-6 shows how the user can initiate a graph-size adjustment for Calcomp plots, by means of a card bearing the key word "HEIGHT" in columns 25-30. An explanation of Message 25 is given in that section.

Message 26

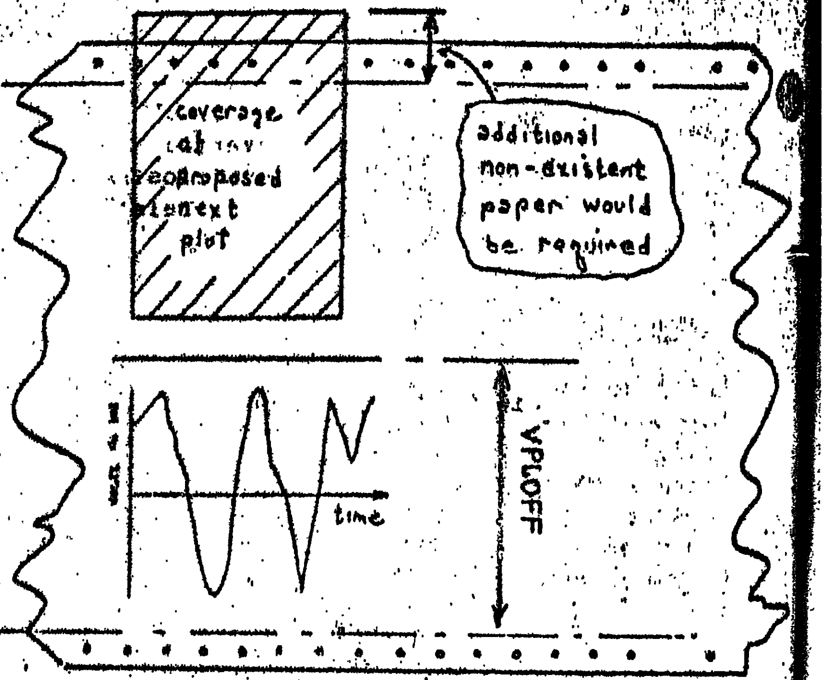
This message should be self-explanatory, except for clarification as to where the limit in question comes from, and why the message talks about a "flatbed" plotter when it is Calcomp plotting which is under consideration!

Conventional Calcomp drum plotters can in theory produce arbitrarily long time axes, it would seem, by simply rolling out more paper. But not everyone is actually using such hardware for the plotting. There are flatbed plotters, wherein plot dimensions are limited by table (bed) size. BPA is an example of such users, having EAI flatbed plotting hardware for which a Calcomp software interface has been provided. The limit on time-axis length, then, is to keep the pen from moving off of the table.

Anyway, for all translations the maximum plot length to be permitted is carried in variable "SZBED" of /BLANK/ . While a default value is assigned in system-dependent module "SYSDEP" of overlay 1, the user can redefine this to any value that he wants, as per Section 1.0c . The default value is of course translator-dependent, with 72.0 inches typical.

Message 27 : VPLOFF (E13.4)

This message will only appear immediately after Message 25, as a qualification. Message 25 was written when the EMTP required that all plots be layed out horizontally on the plotting paper. But since then, vertical spacing (one or more plots above another) is also possible. See Rule 9 of Section 1.10-A. In the illustration at the right, "VPLOFF" is the offset height as printed in this message; it accounts for vertical space which has already been used by one or more preceding plots.



Messages 28-30

Self-explanatory.

Message 31 : HPI (E15.5), HMIN (E15.5), HMAX(E15.5)

The three variables which are printed out as part of the message are as read from columns 5-7, 8-11, and 12-15 of the plot card in question. See Point 3 of Section 1.10-B for further explanation. One of the three illegal conditions listed below has been noted:

a) HPI $\leqslant$ 0.0 —— The scale of the time axis of the plot can not be negative or zero.

b) HMAX $\leqslant$ 0.0 —— The ending time "HMAX" can not be negative or zero.

c) HMAX $\leqslant$ HMIN —— It is impossible for the plot to end (at end-time "HMAX") before it begins (at beginning-time "HMIN").

Message 32

Self-explanatory.

Message 33

Plotting overlay 31 is variably dimensioned automatically, whenever the user redimensions the EMTP as per Section 0.6. But because the computer code (machine instructions) for plotting is longer than that of the longest solution overlay, not all of /LABEL/ is available for dimensioned working space within plotting. It is module "VDOV31", generated by the variable-dimensioning program, which reserves the working space for plotting —— a block of memory equal to the length of /LABEL/ minus a constant offset (which approximately compensates for the extra length of the code of this overlay). If this resulting space (never allowed to be less than unity by the variable-dimensioning program) is insufficient for plotting purposes, the plot request is simply cancelled, as per the text of Message 33.

The solution to the dilemma, of course, is to simply redimension the EMTP as per Section 0.6 . Since it is only the total length of /LABEL/ which matters, it is immaterial which of the independent lists are used to provide for the increased storage.

It should be emphasized that the number of points to be plotted on any one graph is not directly related to the appearance of Message 33. The EMTP is capable of plotting an infinite number of points on any one graph, since the working space is used only as a buffer, to be dumped onto logical unit number 9 if it should ever become full. No, Message 33 indicates a more fundamental problem: the EMTP does not even have enough working space to set up the just-mentioned buffer. This particular program version which generated Message 33 must really be dimensioned way down, designed to run in a very small memory partition.

Message 34

Self-explanatory. The EMTP simulation of course begins at time zero, and continues through time "TMAX" (floating-point miscellaneous data parameter). But the user's last-read plot-request card wanted a plot to begin and end at the times which are incorporated into the message text; these times (as read from columns 8-11 and 12-15, respectively) define an interval which does not include any times for which the solution has been found.

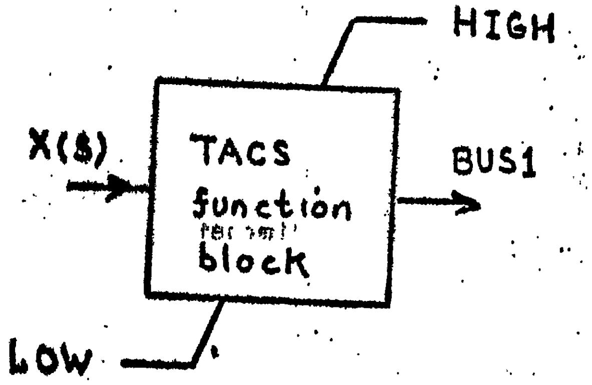
Message 35

This message signals the commencement of the averaging of successive plot points (for purposes of plotting only), for one of the curves of the last-read plot request card. The limiting number of oscillations (before such averaging is instituted) can be chosen at will by the user, as per Section 1.0c . For an example of an EMTP solution which would institute smoothing were the oscillation limit not disabled, see Section 1.40-C , "Remarks on opening section". This phenomena of "spurious mathematical oscillations" is further discussed in the EMTP memorandum dated November 12, 1975.(Reference 8).

Messages 36-37

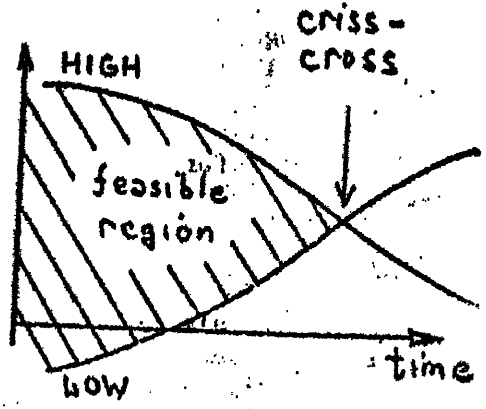
The user is not allowed to stretch the time axis of a printer plot out so as to cover more lines on the paper than there are data points in the curve being plotted. If such an illegally-long printer-plot request is made, the printer plot will be truncated at the aforementioned limit, as per the text of Message 36 or Message 37.

As for the rationale behind this line limit on printer plots, it just seemed like a good way of at least bounding the amount of wasted paper, in case the user makes a gross scaling error on his time axis. "Save a tree in Oregon," as the paper-recycling sign at SCI in Palo Alto used to read. Some computers or compilers may not allow a line limit on the printed output, so hundreds or even thousands of pages of extraneous output could conceivably be generated if one were not careful. Yet, by bounding the number of printed lines by the number of time steps of the simulation, at least a meaningful amount of computation goes along with each line of output; an astronomical number of output lines (e.g., 100000) then is not possible, because the user could never afford to run such a simulation that long to generate the raw data points! Further, such a limit should in no way interfere with production plotting usage, for it makes no sense for the user to plot fewer than one point of a curve per printer line. Maximum time-axis resolution is reached with one output plot point per printer line; it would only look worse, and confusing, if fewer than one point of the curve were outputed for each printer line.



Message 38 : BUS1 (A6)

This message will be printed for TACS function block "BUS1" if there is trouble with the limits which have been specified by the user. See Section 8.5.3 for rules about limits. In the case of two variable limits as in the sketch ("LOW" and "HIGH" are themselves TACS variables), the whole concept becomes inconsistent if the numerical value of "LOW" should ever exceed that of "HIGH". Such a contradictory situation is referred to as "criss-crossing of the limits." Rather than terminate the simulation with a fatal error stop in this case, Message 38 will appear as a warning. The user is advised to rethink his problem formulation, should he see this message. A fatal EMTP error stop really might have been more appropriate, because at the instant this message is printed, the problem as posed by the user has no solution.



Message 39 :

Message 40 : BUS1 (A6), N1 (I4)

This message indicates an error in preparation of the TACS output-variable specification card of Section 8.5.6 . The 6-character alphanumeric name "BUS1" is somehow in error. There is no such TACS variable, so the output request is being ignored (no such variable will be printed or plotted).

Message 42 : LSYN (I4), N5 (I4)

Rather than being just an informative message, this is also a temporary fatal rror stop (FORTRAN "STOP" statement located in module "OVER5"). The message exists only because the dynamic synchronous machine (S.M.) code of Section 1.62 is not yet variably-dimensioned. See the end of Section 1.62 for a full discussion of this dimensioning problem. If the user really more than "N5" S.M. busses, and if he has selected List #17 size "LSYN" larger than this on purpose, then there is problem; changes to the EMTP FORTRAN code will be required, in order to run the data case of interest. On the other hand, if "LSYN" was simply chosen to be different than the printed value f "N5" by accident, then a very simple solution exists : redimension the EMTP as per S ction 0.6, using "LSYN" equal to the printed value of "N5" . As of October, 1977 (UTPF having "M20." idents), "N5" was equal to two.

Message 43 : N1 (I5), BUS1 (A6), N2(I5), N3 (I5)

This message implies an erroneous punch in column number "N1" of a Class 5 synchronous machine (S.M.) data card, as described in Section 1.62 . Variable "BUS1" will indicate which of the three types of shaft outputs is involved —— either "ANGLE " , "SPEED " , or "TORQUE" . The third of these actually does not apply to the single mass which is listed, but to the connection between this mass and the following one. But the requested output variable simply does not exist, so can not be provided by the EMTP; the shaft system does not have this many masses (only "N3" masses exist). Presumably the user has punched the wrong column of the data card, due to carelessness.

Message 43 was written before the alternate, expanded format for Class 5 S.M. data was made available. If the expanded format is being used, eleven (11) must be subtracted from the printed value of "N1" in order to get the correct column number.

Message 44 : BUS1 (A6)

First, read Section 8.5.3 on limiters. The TACS-calculated dc steady-state calculation is a one-pass operation. Depending on the ordering of the blocks, a limit may be superimposed on a block either after or (preferably) before its value is used as input to another block. During the calculation at t > 0.0 , the effect of the limit is at worst delayed by one time step, as discussed in 8.5.3 . But for the steady-state initialization at t = 0.0 , there is no second chance, and should a limiter be found to operate at t = 0.0 , the user has to make sure that all other blocks depending on the output of this limiter have indeed been calculated using the limited value.

Message 45 : N1 (I5), N4 (I1)

The same data card as has already been discussed in Message 43 is at issue here. But here the complaint is that the nonzero output-request punch "N4" is neither a one nor a two —— the only two digits which have meaning. The second paragraph of Message 43 applies here, also.

Message 46 : JPOINT (I5), IVAR (I5), ISM (I5)

The text should be self-explanatory. The end of Section 1.62 contains complete documentation showing how the limiting program dimension might be increased, should this really be necessary. In the nomenclature of that section, "P" has value "JPOINT" as printed out in Message 46 .

Message 47 : EPSILN (E13.2), NIAMAX (I5), N1 (I5), EPSDIV (E13.2)

Paragraphs number one and number three of Message 47 are always printed; paragraph number two will only be printed in the case of numerical blow up (not in the case of insufficient number of iterations).

Further comments about the "PARAMETER FITTING" option which has experienced trouble will be found in Section 1.62 , where the synchronous machine (S.M.) component is fully described; see Class 2 data cards, Point c . Message 47 might possibly be printed twice for each physical generating unit (four times for a dual machine), since d-axis parameters are fitted separately from q-axis parameters.

It should be noted that "EPSILN" is the floating-point miscellaneous data parameter of Section 1.0h , so it is under user control. The iteration limit "NIAMAX" can be redefined by means of the "TOLERANCES" card of Section 1.62 (Class 2 data cards, Point b). The blow-up tolerance "EPSDIV" is not under user control; it is hard wired into module "SMPFIT" , with the value 0.5 being used as of October, 1977 (empirically set by Vladimir).

As per the final paragraph, execution will continue without parameter fitting for this axis of this machine. The subsequent simulation should be generally valid ---- at least as valid as the input data. Yet the user is advised to scrutinize his machine parameters, since the most frequent cause of divergence seems to be erroneous (either physically-unrealizable or otherwise highly improbable) data. Vladimir could tell you an interesting story about the data parameters used in Reference 18!

Message 48

The explanation of Message 48 shall be limited, due to plans which will eliminate the entire complication in the near future. Rather than use pairs of node names for reference purposes, we intend to use a branch name, when we can find the time to make the change.

Message 48 requires no explanation when it is working properly. Were it not for reference-component usage of the saturable "TRANSFORMER" component of Section 1.25 , there would never be any ambiguity or confusion.

But the saturable "TRANSFORMER" component of Section 1.25 will often produce "false" warnings, which the user should learn to recognise and ignore. The problem is that, internal to the EMTP, a saturable "TRANSFORMER" is not a transformer at all; only the user thinks of it this way. At data-input time (in "OVER2"), this higher-level, conceptual interpretation is broken down into low-level EMTP building blocks:

1. One series R-L-C branch for the primary leakage (R_1 , L_1).

2. A series R-L-C branch for the magnetizing resistance R_{mag} , should the input data field be nonzero.

3. A Type-98 pseudo-nonlinear inductance element for the nonlinear magnetizing branch, if any.

4. N-1 separate pairs of branches, each represented by [A] and [B] matrices. Here "N" is the number of windings, and there is one such 2 x 2 matrix representation for each 2-winding ideal transformer (plus non-primary leakage) of the equivalent circuit.

It is this fourth item which frequently triggers the false warnings, for saturable "TRANSFORMER" components which use the reference-component option (field "BUS3" of the lead data card being nonblank). The pair of node names within Message 48 will correspond to $BUS1_2$ and $BUS2_2$ (see equivalent circuit) in the case of a 2-winding transformer. For a 3-winding unit, there may also be the second pair of node names, for the tertiary ($BUS1_3$ and $BUS2_3$) .

Point to be made : The reference usage really does exist, internal to the EMTP. But the user had nothing to do with it, and should not be concerned. The user should in the case of saturable "TRANSFORMER" components disregard the warning about which elements were rejected, and which ones were used; the EMTP never makes a mistake in this case (famous last words?)

Message 49

This message will be printed only for a "STATISTICS" or "SYSTEMATIC" data case (see Class 3A and Class 3E , Section 1.4) in which there is just one energization. This situation is user-controlled, with integer miscellaneous data parameter "NENERG" (see Section 1.0h) equal to unity. Of course no sort of meaningful tabulation is possible, for the case of just a single energization. Yet the EMTP will perform all of the conventional postprocessing of overlay #29 (module "SUBR29") ——— all except for the variance (and standard deviation) calculation. Division by NENERG - 1 = 0 would be required, and this is being bypassed; Message 49 is being printed instead.

Message 50

It is highly unlikely that the EMTP user will ever see this message as part of his EMTP line printer output. Only if his Program Maintenance people have redimensioned his EMTP version so as to allow just a single mass ——— only in this case might there be trouble. In terms of the COMMON /SMACH/ storage which is described at the end of Section 1.62 , it is arrays E11(M,M,2C) through E22(M,M,2C) which are used for the armature current storage. Using the "M20." UTPF dimensions of M = 10 and C = 2 , this provides a working region of 1600 cells, while only a maximum of 24 are needed. But if "M" were set to unity, note that only 16 working spaces would be available, and there would be trouble (for cases with dual machines). It should be emphasized that the time-step-loop output is unaffected by any such lack of temporary working space; the subsequent simulation will be valid; Message 50 only refers to storage which is needed for steady-state printout purposes.

Message 51 : N1 (I4), NTOT (I4), NCHNR (I6)

This message is largely self-explanatory: not much more will be added here. Message 51 will generally only be seen in conjunction with a case which has a large number of switches and/or pseudo-nonlinear elements; the terminal nodes of such elements are constrained to be renumbered last, thereby increasing the fill-in during simulated triangularization. It should be emphasized that it is the renumbering attempt for the transient network (as used in the time-step loop) which has broken down ——— not the renumbering attempt for the steady-state network. Should the same storage inadequacy occur during renumbering for the steady-state phasor solution, a fatal EMTP error stop (with a "KILL" code, as in Section 2.4) will result.

Note that the EMTP is recovering from the storage inadequacy, as per the second paragraph of Message 51 . Yet this may be only a temporary reprieve. There is a fundamental storage inadequacy, and a subsequent EMTP error stop during either the steady-state renumbering or the Y-matrix factorization or formation (for the time-step loop) is not unlikely. It is dependent List #99 (of the summary statistics which terminate each case; see Section 2.3 or 2.4) which is of inadequate size for the user's data case. EMTP redimensioning of Section 0.6 is recommended, with larger numbers for List #5 and/or List #8 . Both of these lists contribute fully (100%) to List #99 .

For illustrative purposes only, the renumbering map NORDER(I) has been shown as NORDER(I) = I , for I=1, NTOT . Of course this is completely problem-dependent.

Message 52 : BUS1 (A6)

This situation may occur after superimposing the dc and ac TACS-calculated steady-state initialization solutions. In this case, neither dc or ac contributions to the output of this block involved the operation of the associated limiter. But when adding the two, it is found that the output value exceeds either lower or higher limits of the block. However, the value of other blocks depending on this output has already been calculated. Read the interpretation of message 44 for more details.

Message 53

Something is grossly wrong, if the user sees Message 53 . Either one or more solutions is garbage, or the user has made an error in specifying his base voltage, or both! Recall that "XMAXMX" of the "STATISTICS" or "SYSTEMATIC" miscellaneous data card (see Section 1.1a) is supposed to be a voltage level (in per unit) which should never be exceeded during any of the energizations. Then, just to be doubly sure, the EMTP multiplies this user-supplied figure by five. Message 53 then results when the user-supplied bound is exceeded by a factor of five or more! So what is wrong? Is "XMAXMX" reasonable? Are the base voltages as defined on the "STATISTICS" or "SYSTEMATIC" output cards (see Section 1.8b) reasonable? Are peak voltages for each energization reasonable? An inconsistency exists in one or more of these three areas.

Message 54 : N1 (I6)

"SOLVSM" is the principal module within the time-step loop (overlay numb r 16) of the SCE synchronous machine (S.M.) code which is described in Section 1.62 . For the simultaneous solution to linear equations which is required, a call to the canned equation-solution module "DGELG" is made. This is an off-the-shelf item which came from the SCE IBM/370 shop, with about 35 comment cards preserved at the beginning of the module. Read these, for a more complete explanation of the Gaussian elimination with complete pivoting which is used.

The basic complaint of Message 54 seems to be that the coefficient matrix of the linear equations is near singular, and that there is troubl in choosing the next pivot element while working on row or column number "N1". The tolerance which is used to measure singularity in this case is actually under user control, by means of the "TOLERANCES" card (see Point b of Class 2 S.M. data, Section 1.62); variable "EPDGEL" is the tolerance for this usage. Has the user tampered with this value, compared with previous successful executions?

In the two years of IBM/CDC (64/60 bit) experience with this SCE S.M. code, Message 54 is not known to have ever been seen ---- despite production usage by a half dozen utilities. Should the user encounter Message 54 for the first time, he is definitely advised to take the line printer output to Program Maintenance for further study.

Message 55 : BUS1 (A6), BUS2 (A6)

The EMTP data case which is now being solved is a "STATISTICS" or "SYSTEMATIC" one (see integer miscellaneous data parameter "NENERG" of Section 1.0h). The base case (with all variances temporarily set to zero) has already been solved and plotted. The EMTP is now reading and processing the output requests for statistical overvoltage tabulation (see Section 1.8b). Any pair of legal node names is allowed, in making a voltage-difference request. But one or more of the user's names ("BUS1" and "BUS2" of the message) does not correspond to any node of the user's network. Is there spelling trouble? Or is there trouble with the positioning of blank characters within the alphanumeric field of width six?

Message 56 : BUS1 (A6)

The last-read data card is not a legal specification for node-voltage outputs as required by Section 1.8a . The name "BUS1" which was read from the data card does not belong to any node of the user's data case. Is there spelling trouble? Or is there trouble with the positioning of blank characters within the alphanumeric fields of width six.

Message 57 : T'_{do} , T'_{qo} , T''_{do} , T''_{qo} , 10*DELTAT (5E15.6)

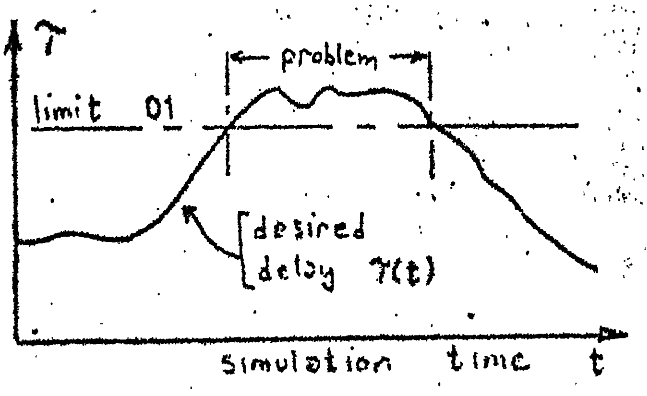
The EMTP is currently inputting dynamic S.M. data in module "SMDATA" or "SMDAT" of overlay number 5, as described in Section 1.62 . For a Type 50, 51, or 59 machine, the third card of Class 3 S.M. data contains transient and subtransient time constants for both axes in columns 1-40 . Now, for usual power system usage, these four time constants will all be much larger than the EMTP time-step size "DELTAT" (read from the floating-point miscellaneous data card of Section 1.0h). For example, UTPF Test Case #90 is further documented in Section 1.62 , where it is seen that the smallest of the four time constants in question is the third; and this has a value of .11782 seconds, which is typically between 100 and 1000 times the normal time-step size. But this factor of ten separation between all time constants and "DELTAT" does not hold for the user's data, as per the Message 57 printout. Was the user aware of his unusual time constants (by large-unit power system standards)? This is just a warning; the simulation will continue as requested (garbage in, garbage out).

Message 58 : BUS1 (A6)

The data case being solved involves TACS modeling, as described in Section 8. . Included is a frequency sensor having name "BUS1" ——— a Type-50 supplemental device (see Section 8.5.5). Recall that this device merely detects the time interval between successive zero-crossings of the input signal, and reciprocates twice this to give an estimate of the instantaneous frequency (whatever that is). But the new frequency which has just been calculated differs from the old one (calculated at the preceding zero-crossing; or possibly left over from the initial condition) by at least fifty percent. Such drastic changes in frequency are not allowed, for they are an indication that the solution is not varying smoothly. Possibly there was a spurious zero-crossing due to "hash" or "noise", and rejection of this latest estimate is based on this assumption. As stated in Section 8.5.5 , "the device will automatically reject higher-frequency non-characteristic oscillations appearing on the main signal." Frequency of the "main signal" is of course defined by the user as the initial frequency which is punched in columns 51-56 of the device data card.

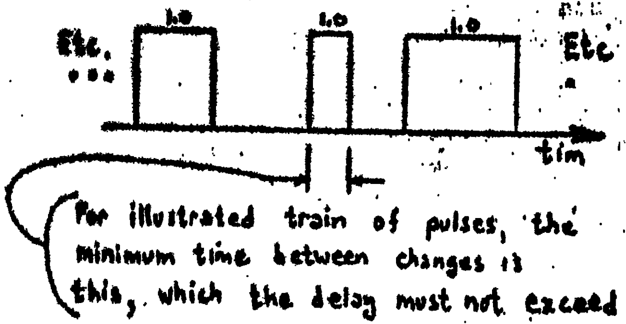
Message 59 : BUS1 (A6), D1 (E13.6)

The data case being solved involves TACS modeling, as described in Section 8. . Included is a transport delay block bearing output name "BUS1" ——— a Type-53 supplemental device of Section 8.5.5 . Recall that the delay can be a variable (dynamically-changing) quantity, since it is the sum of a fixed delay and a named delay. Well, this total delay was never supposed to exceed the user-supplied bound of "D1" . But it did. The transport delay block needs more storage, but can not get it (dynamic expansion of the tables is not possible at this time). The simulation will continue, but is erroneous in that delays are strictly limited to time "D1" . Note that only this first instance of such saturation or clipping will be noted on the line printer. A plot would reveal the full story.



Message 60 : BUS1 (A6), D1 (E13.6), D2 (E13.6)

The data case being solved involves TACS modeling, as is described in Section 8. . Included is a pulse transport delay block bearing the output name "BUS1" ——— a Type-54 supplemental device of Section 8.5.5 Recall that the delay must never exceed the time between successive changes in the input signal. Phrased another way, never more than one variable change can be stored within the history of the delay; it only has scalar storage (unlike the Type-53 block which has vector storage). The last change has to propagate through the delay block and out the other end before a new change is allowed in the front end. But this limitation has not been observed in the user's case.


Etc. ...
1.0
1.0
1.0
Etc
time
For illustrated train of pulses, the minimum time between changes is this, which the delay must not exceed

If the user sees Message 60, possibly it is an indication of trouble elsewhere in the system. That is, problems elsewhere make for an erroneous input signal to the block, which in turn triggers this warning message. After all, garbage in, garbage out. Bob Hasibar (of BPA, Route EOGB) found this to be the case with his big ac/dc converter simulations. On the other hand, if the input signal and all other parameters of the block seem to be valid, then perhaps the user must consider switching from the Type-54 device to the Type-53 device.

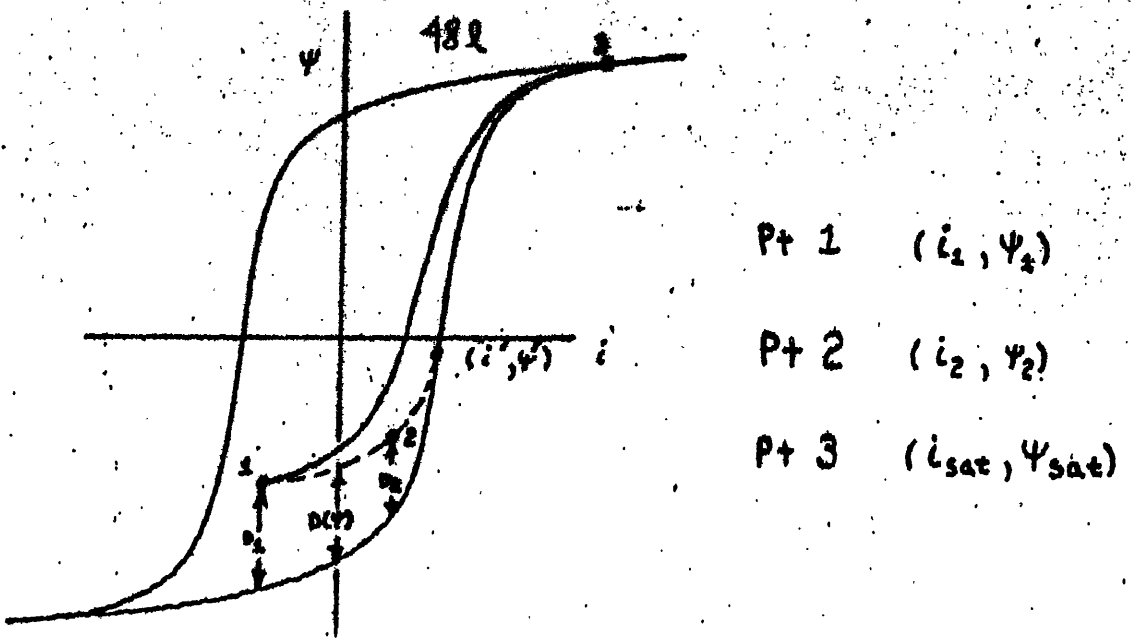
Message 61 : BUS1 (A6), T (E14.6)

Similar to Message 59. In this case, the dynamically-changing value of the delay has become negative. So as not to transform this type-53 device into a crystal ball, the lower bound on the variable delay value is 0.0 .

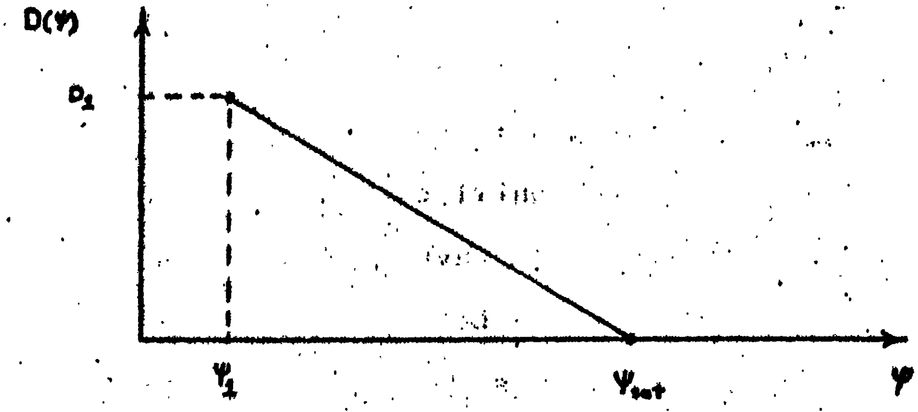
Message 62 BUS2(A6), BUS2(A6),

```
NOTE <---- FOR THE TYPE-96 HYSTERETIC INDUCTOR WHICH CONNECTS BUS 'A6 ' TO 'A6 ', A TRAJECTORY WAS
           INITIALLY CREATED WHICH WOULD HAVE CAUSED OPERATION OUTSIDE THE MAJOR HYSTERESIS LOOP. THE
           TRAJECTORY HAS BEEN MODIFIED TO PREVENT THIS. ACCURACY OF THE RESULTS SHOULD BE UNAFFECTED.
```

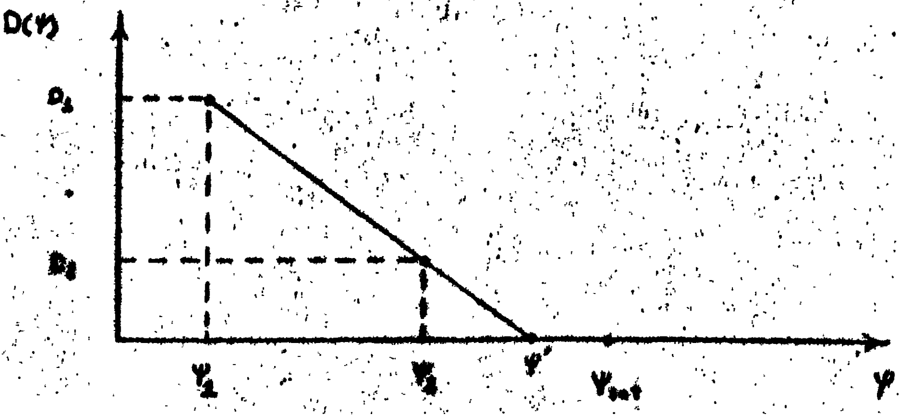
This message is associated with the way minor loop trajectories are created for a type-96 hysteretic inductor. A minor loop trajectory is specified in terms of the major hysteresis loop trajectory by constraining how the distance between the traj ctories (along a line of constant current) varies as operation proceeds along th minor loop. This is shown below.



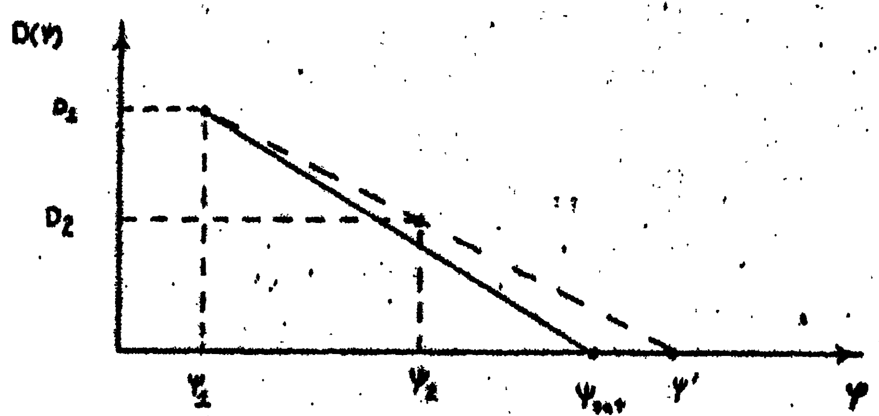
In this figure the solid line form pt. 1 to the saturation point indicates a minor loop trajectory, which begins at pt. 1 and extends out into the saturation region. Notice that as ψ increases from ψ_1 to ψ_{sat}, $D(\psi)$ decreases from D_1 to 0. This decrease occurs linearily and can be represented in the $D(\psi)$ - ψ plan as shown.



There are other instances in which it is known (from a knowledge of past behavior of the core) that the minor loop trajectory should pass through pt. 2. This requires the $D(\psi)$ function shown below.



Notice that in the first instance the minor loop joined the major loop ($D(\psi)$ became zero) right at the saturation point, while in the second instance the minor loop joined the major loop at the point (i', ψ'). This is all fine. However, consider the following case.



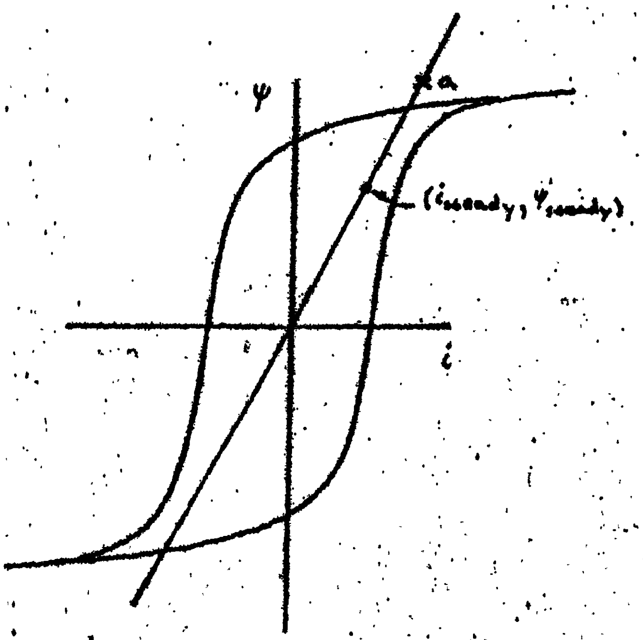
Suppose pt. 2 was located as shown in the above figure. Following the same algorithm as previously used would lead to a function $D(\psi)$ as shown by the dashed line. Notice that now $\psi' > \psi_{sat}$, which indicates that the minor and major loop trajectories would not intersect until somewhere beyond the saturation point. This is impossible, however, since beyond the saturation point there is no difference between major and minor loop trajectories (because of the single valued nature of hysteresis in the saturation region). In this case a different algorithm is chosen, which leads to the trajectory shown as a solid line. For this trajectory the major and minor loop will intersect right at the saturation point.

The occurrence of mesage 62 indicates that this last case described has occurred. It is anticipated that this case should occur very seldom. Should it occur the results obtained may be considered as accurate as any other results obtained using type-96 hysteresis modeling. Unless you receive this message quite often it may simply be ignored. If however, you do receive this message quite often please inform program maintenance. It may be necessary to rethink some aspects of the hysteresis algorithm

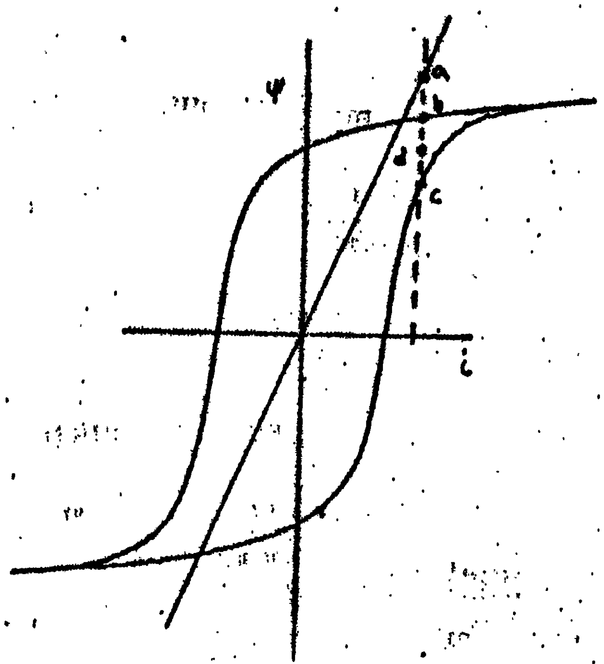
<u>Message 63</u> I, BUS(K), BUS(m), CI1, CURR(I), D14, D13, D12

```
NOTE ---- NONLINEAR ELEMENT NUMBER  I4 IS A TYPE-96 HYSTERETIC INDUCTOR WHICH IS CONNECTED
          BETWEEN BUSSES  ' A6    '  AND  ' A8  ' .   THE INITIAL FLUX-CURRENT POINT AS FOUND BY THE
          PHASOR STEADY-STATE SOLUTION HAS BEEN OBSERVED TO LIE OUTSIDE THE USER-DEFINED MAJOR HYSTERESIS LOOP, HOWEVER.
          THE INITIAL FLUX IS    E14.4       AND THE INITIAL CURRENT IS    E14.4     .   THE EMTP SHALL NOW ALTER THIS
          JUST-PRINTED FLUX SO AS TO MAKE IT LEGAL, WHILE HOLDING THE CURRENT CONSTANT.   THE LINE OF CONSTANT CURRENT
          INTERSECTS THE USER-SUPPLIED MAJOR HYSTERESIS LOOP AT TWO POINTS (POSSIBLY EQUAL, IF THE CURRENT IS LARGE
          ENOUGH).   THE  'UPPER'  IS CUT AT FLUX VALUE      E14.5   ,   AND THE  'LOWER'  AT FLUX VALUE  E14.5   .
          THE INITIAL FLUX SHALL BE TAKEN BY THE EMTP TO BE THE AVERAGE OF THESE, WHICH HAS FLUX VALUE   E15.5
```

This message indicates a discontinuity in the solution of a problem involving a type-96 hysteretic reactor at time zero. It is a result of two different methods used to model the type-96 flux-current behavior. During a steady-state solution the type-96 is represented as a linear element, defined by the point i_{steady}, ψ_{steady}, (see section 1.3I) as shown at right. It is possible for the initial flux-current point to lie anywhere on the line, even outside of the major hysteresis loop, as shown by point a. The difficulty arises at time zero when the transient solution begins. During the transient solution the actual hysteresis behavior is modeled, and operation outside of the major loop is never allowed. Therefore an initial point, calculated by a steady-state solution, which lies outside of the major loop violates this basic



rule. In such a case it is necessary to either move the initial point inside of the loop or terminate the run at this point. It was decided to move the point within the major loop, print message 63, and leave the user with the responsibility of deciding for himself whether the changes made are acceptable or not.



The method used to move the initial point within the major loop is the following. The line of constant current is drawn through the initial point and its intersections with the upper and lower half of the major hysteresis loop are calculated (points b and c). The average of these points (point d) is then taken as the initial point. Notice that if the value of initial current is large enough ($\geqq i_{sat}$) then points b, c, and d are all the same point, namely the new initial point. This same discussion holds, of course, for an initial point in the third quadrant.

As mentioned earlier it is the users responsibility to decide if the changes made are acceptable in this case. It is very strongly suggested that the user make legitimate changes which will cause all such messages to disappear. It is important to realize that transients due to sudden changes in flux (like are being made here) may die out very slowly. A further discussion of this problem and some suggestions for correcting it are contained in Section 1.31 .

2.2c Connection Discontinuities During Solution

The closing and/or opening of switches, of switched elements, and of flashover elements is noted by means of printed messages, as the solution proceeds. Such messages thus interrupt the regular time-step printout of solution variables as described in Section 2.2a . The message texts are as follows, for the different element types which have such printout. Where sample node names are needed, the names "NODE 1" and "NODE 2" are used. Where a floating-point number is printed, the FORTRAN format specification (see Section 0.7) is used.

Ordinary Switch (Section 1.40)

The message for closure:

SWITCH 'NODE 1' TO 'NODE 2' CLOSED AFTER $\boxed{\text{E12.5}}$ SEC.

A time of -1.0 seconds is used to symbolically indicate a switch which has been closed in the steady-state.

The message for opening:

SWITCH 'NODE 1' TO 'NODE 2' OPEN AFTER $\boxed{\text{E12.5}}$ SEC.

Switched-Inductance Element (Section 1.41)

Messages for opening and closing of the saturation branch are identical to those for the ordinary switch above.

Switched-Resistance Element (Section 1.42)

Messages for opening and closing of switched-resistance branch are identical to those for the ordinary switch above. In addition, immediately above the opening message, will be found the added information concerning energy dissipation:

ENERGY ABSORBED IN SWITCHED RESISTANCE 'NODE 1' TO 'NODE 2' $\boxed{\text{E15.6}}$

The printed energy is that dissipated during the most recent interval of time that the resistance was connected (the interval between closing and opening messages).

Diode, Valve or TACS-controlled Switch (Sections 1.43, 1.44, 1.45)

Messages for the opening and closing of a type-11, type-12, or type-13 TACS-controlled switch are similar to those for the "Ordinary Switch" just described. But one difference is that here such messages must be explicitly requested by the user by the column-79 parameter "ECHO". The general form of the message is:

$$\left\{\begin{matrix}\text{DIODE}\\ \text{VALVE}\\ \text{GAP}\\ \text{SWITCH}\end{matrix}\right\}\ \text{'NODE 1' TO 'NODE 2'}\ \left\{\begin{matrix}\text{OPENING}\\ \text{CLOSING}\end{matrix}\right\}\ \text{AFTER}\ \boxed{\text{E12.5}}\ \text{SEC.}$$

Type-94 SiC Surge Arrester (Section 1.34)

Messages associated with the firing and clearing of a Type-94 modern-styl SiC surge arrester component are similar to those for the switched-resistance element described above:

```
   ARRESTER  'NODE 1'  TO  'NODE 2'  FLASHOVER AT TIME    E13.5    SEC.
   ARRESTER  'NODE 1'  TO  'NODE 2'   CLEARED  AT TIME    E13.5    SEC.
                 PER UNIT ENERGY DISSIPATED =    E14.6
```

The third line (energy dissipation) always immediately follows the second line; the first line may be separated from these by conventional time-step loop printout, of course. The per unit system as used in this message for nergy dissipation is explained at the end of Section 1.34 .

Pseudo-Nonlinear Resistance (Section 1.28)

The same message text applies both to flashover and to opening, with only the segment number "XX" differing:

Flashover: Segment number XX = JUMP > 0
(see columns 39-44 of input data card).
Opening: Segment number XX = 0

The message itself reads as follows:

```
TYPE-99 N.L. ELEM 'NODE 1' TO 'NODE 2' AT T= E12.4 BEGINS OPERATION ON
SEGMENT XX.
```

Nonlinear Resistance (Section 1.32)

As per Section 1.32, the piecewise-nonlinear resistance element can only flash over; it is thereafter permanently connected. The flashover message reads as follows:

```
TYPE-92 NONLINEAR V-I FROM 'NODE 1' TO 'NODE 2' FIRES AT TIME |E14.6| SEC.
```

2.2d Printout of Storage and Running-Time Statistics

At the conclusion of the solution of each data case, a half page of printout provides a summary of storage and running-time requirements. Refer to the sample output of Section 2.3 . In summary, the following will be found:

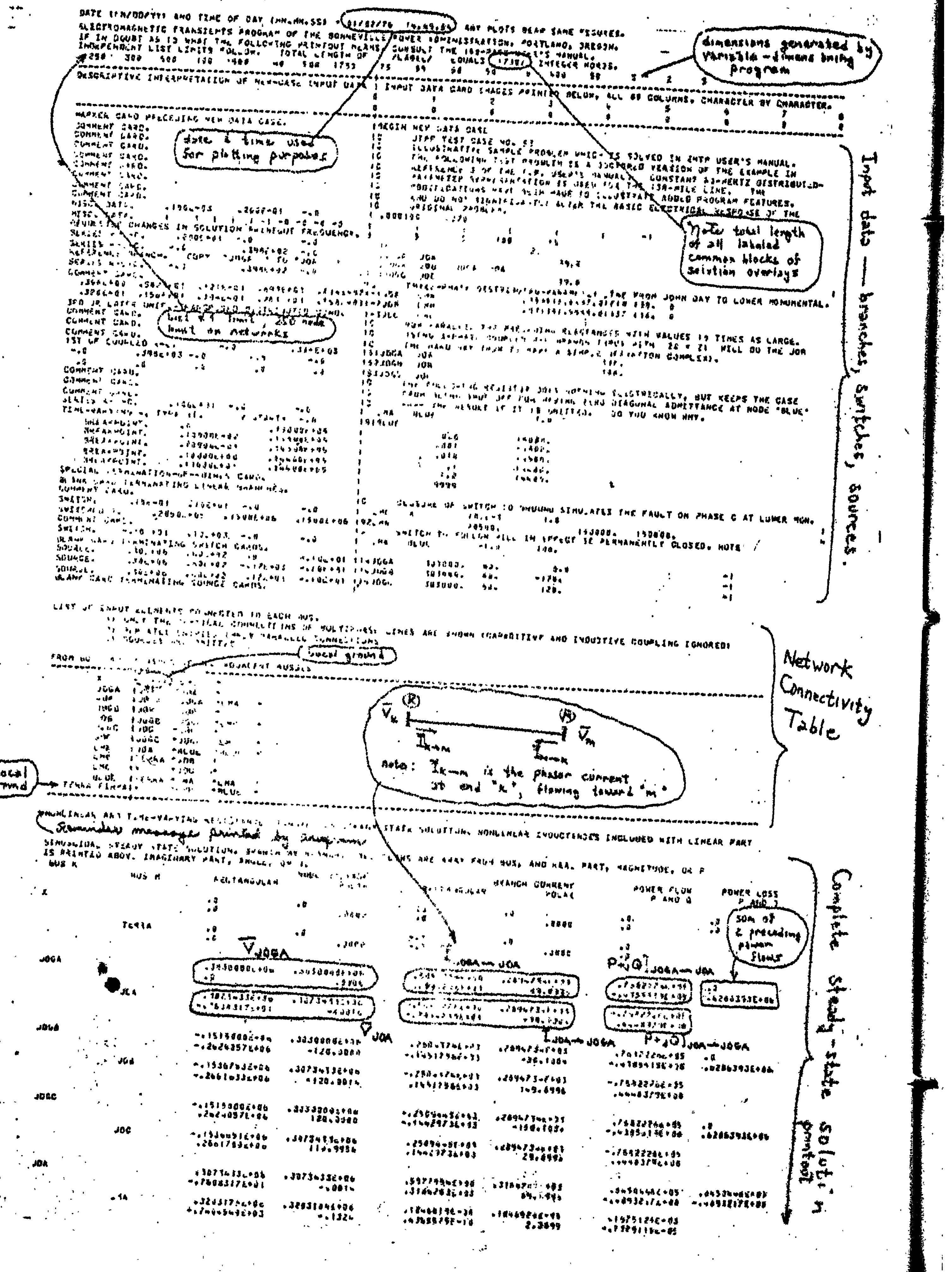
1. Current program dimensioned limits for all tables. These are identified by "list number," row by row. as per Section 0.6 .
2. Actual number of cells of these tables which the current problem has used.
3. Computer running time for this case. Central processor (CP), input-output (I/O), and total (CP + I/O) are all three printed, for each of 5 major subdivisions of the program. Sums of these are also provided, giving the total computer time attributable to execution of the case just finished. Yet caution should be used in interpreting these figures, due to variations between different computer installations. Some computers may not have a CP figure available, in which case zero contribution for this component will generally be observed. See Program Maintenance if there are questions.

2.3 Annotated Printer and Plotter Output of Sample EMTP Test Problem

The four pages which follow show photo-reduced line printer output and Calcomp plots which resulted from the EMTP solution of a sample test problem. Rather than being a meaningful production problem, this case was artificially set up for purposes of this illustrative, tutorial usage only.

It should be mentioned that the output shown came from solution on BPA's CDC-6500, with plotting done on an EAI flatbed plotter having a print head. Minor variations in the appearance of the results might be expected, were a diff rent computer and different plotter used to solve the data case.

446



```
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) = 01/02/76  14.49.55   ANY PLOTS BEAR SAME FIGURES.
ELECTROMAGNETIC TRANSIENTS PROGRAM OF THE BONNEVILLE POWER ADMINISTRATION, PORTLAND, OREGON.
IF IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE 180-PAGE USER'S MANUAL.
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF  /LABEL/   EQUALS  17387  INTEGER WORDS.
  250   300   500   130   1400   40   500  1752   75   99   50   50   9   450   50   3   2   3
-------------------------------------------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA | INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER.
                                                  0         1         2         3         4         5         6         7         8
                                                  0         0         0         0         0         0         0         0         0
-------------------------------------------------------------------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.              |BEGIN NEW DATA CASE
COMMENT CARD.                                     |C        JTPP TEST CASE NO. 57
COMMENT CARD.                                     |C        ILLUSTRATIVE SAMPLE PROBLEM WHICH IS SOLVED IN EMTP USER'S MANUAL.
COMMENT CARD.                                     |C        THE FOLLOWING TEST PROBLEM IS A DOCTORED VERSION OF THE EXAMPLE IN
COMMENT CARD.                                     |C        REFERENCE 3 OF THE E.P. USER'S MANUAL.  CONSTANT 60-HERTZ DISTRIBUTED-
COMMENT CARD.                                     |C        PARAMETER REPRESENTATION IS USED FOR THE 138-MILE LINE.   THE
COMMENT CARD.                                     |C        MODIFICATIONS WERE MADE TO ILLUSTRATE ADDED PROGRAM FEATURES,
COMMENT CARD.                                     |C        AND DO NOT SIGNIFICANTLY ALTER THE BASIC ELECTRICAL RESPONSE OF THE
COMMENT CARD.                                     |C        ORIGINAL PROBLEM.
MISC. DATA.       .100E-03    .260E-01    .0      | .000100    .026
MISC. DATA.       1  1  1  1  1 -1  0  0  0  0    |  1    1    1    1    1   -1
REQUESTED CHANGES IN SOLUTION PRINTOUT FREQUENCY. |  5    2  100    5
SERIES R-L-C.           .200E+01   .0       .0    |                  2.
SERIES R-L-C.     .0               .394E+02  .0   |  JOA
REFERENCE BRANCH.    COPY  JOGB   TO  JOB         |  JOB    JOGA  JOA
SERIES R-L-C.     .0               .394E+02  .0   |  JOC                      39.4
COMMENT CARD.                                     |C THREE-PHASE DISTRIBUTED-PARAMETER LINE FROM JOHN DAY TO LOWER MONUMENTAL.
 .396E+00  .582E-01  .121E-01  .493E+01  [illegible]|-1JOA  LMA   [illegible]  138.  0
 .329E+01  .150E+01  .394E-01  .281E+01  [illegible]|-2JOB  LMB   [illegible]  138.  0
3RD OR LATER UNIT, CHARGE AND DISTRIBUTED LINE.   |-3JOC  LMC
COMMENT CARD.                                     |C  NOW PARALLEL THE PRECEDING REACTANCES WITH VALUES 10 TIMES AS LARGE,
COMMENT CARD.                                     |C  USING 3-PHASE COUPLED R-L BRANCH INPUT WITH  Z0 = Z1  (WILL DO THE JOB
COMMENT CARD.                                     |C  THE HARD WAY THEN IF HAVE A SIMPLE ITERATION COMPLEX).
1ST OF COUPLED R-L.      .0        .394E+03       |51JOGA  JOA                       394.
 .0     .394E+03  .0       .0       .394E+03      |52JOGB  JOB                       197.
 .0     .0        .0       .0       .0            |53JOGC  JOC                       186.
COMMENT CARD.                                     |C  THE FOLLOWING RESISTOR DOES NOTHING ELECTRICALLY, BUT KEEPS THE CASE
COMMENT CARD.                                     |C  FROM BEING SHUT OFF FOR HAVING ZERO DIAGONAL ADMITTANCE AT NODE "BLUE"
COMMENT CARD.                                     |C  WHEN THE RESULT IF IT IS OMITTED.   DO YOU KNOW WHY.
SERIES R-L-C.          .100E+01    .0     .0      |  LMA   BLUE          1.0
TIME-VARYING R, TYPE 91.    T START=  .0          |91BLUE
    BREAKPOINT.      .0          .15000E+06       |            0.0       15000.
    BREAKPOINT.      .13000E-02  .11400E+05       |            .001      11400.
    BREAKPOINT.      .10000E-01  .14500E+05       |            .010      14500.
    BREAKPOINT.      .10000E+00  .14400E+05       |            .1        14400.
    BREAKPOINT.      .11000E+00  .14400E+05       |            1.1       14400.
SPECIAL TERMINATION-OF-POINTS CARD.               |            9999
BLANK CARD TERMINATING LINEAR BRANCHES.           |
COMMENT CARD.                                     |C  CLOSURE OF SWITCH TO GROUND SIMULATES THE FAULT ON PHASE C AT LOWER MON.
SWITCH.          .150E-01   .150E+01   .0    .0   |  LMC                  .015   1.0
SWITCHED R.         .2850E+05   .15000E+06  .15000E+06 |92LMA             28500.       150000.   150000.
COMMENT CARD.                                     |C  SWITCH TO FOLLOW WILL IN EFFECT BE PERMANENTLY CLOSED. NOTE
SWITCH.          -.10E+01   .10E+03   .0      .0  |  LMA   BLUE          -1.0       100.
BLANK CARD TERMINATING SWITCH CARDS.              |
SOURCE.     .10E+06   .60E+02   .0   -.10E+01     |14JOGA    101000.   60.        0.0         -1
SOURCE.     .10E+06   .60E+02  -.12E+03  -.10E+01 |14JOGB    101000.   60.       -120.        -1
SOURCE.     .10E+06   .60E+02   .12E+03  -.10E+01 |14JOGC    101000.   60.        120.        -1
BLANK CARD TERMINATING SOURCE CARDS.              |

LIST OF INPUT ELEMENTS CONNECTED TO EACH BUS.
        1) ONLY THE PHYSICAL CONNECTIONS OF MULTIPHASE LINES ARE SHOWN (CAPACITIVE AND INDUCTIVE COUPLING IGNORED)
        2) REPEATED ENTRIES IMPLY PARALLEL CONNECTIONS
        3) SOURCES ARE OMITTED
FROM BUS NAME |  NAMES OF ALL ADJACENT BUSSES
--------------------------------------------------------------------
      X       | TERRA *
      JOGA    | TERRA *JOA  *
      JOA     | JOGA  *JOGA *LMA  *
      JOGB    | TERRA *JOB  *
      JOB     | JOGB  *JOGB *LMB  *
      JOGC    | TERRA *JOC  *
      JOC     | JOGC  *JOGC *LMC  *
      LMA     | JOA   *BLUE *BLUE *
      LMB     | TERRA *JOB  *
      LMC     | JOC   *
      BLUE    | TERRA *LMA  *LMA  *
      TERRA   | X     *JOGA *JOGB *JOGC *BLUE *
--------------------------------------------------------------------
NONLINEAR AND TIME-VARYING RESISTANCES [illegible] STEADY STATE SOLUTION, NONLINEAR INDUCTANCES INCLUDED WITH LINEAR PART
SINUSOIDAL STEADY STATE SOLUTION, BRANCH BY BRANCH.  ALL FLOWS ARE AWAY FROM BUS, AND REAL PART, MAGNITUDE, OR P
IS PRINTED ABOVE, IMAGINARY PART, ANGLE, OR Q.
 BUS K      BUS M       NODE VOLTAGE                     BRANCH CURRENT                 POWER FLOW       POWER LOSS
                      RECTANGULAR      POLAR        RECTANGULAR       POLAR           P AND Q          P AND Q
 X
                        .0            .0            .0            .0                .0               .0
                        .0            .0000         .0            .0000             .0               .0
            TERRA
                        .0            .0            .0            .0                .0
                        .0            .0000         .0            .0000             .0
 JOGA
                        .35000000E+06 .35000000E+06 [illegible]   .28947930E+03     .75827754E+05    .0
                        .0            .0000         [illegible]   43.0332           [illegible]      .62863939E+06
            JOA
                        .10731133E+06 .10734911E+06 [illegible]   .28947931E+03     [illegible]
                        -.63431790E+01 -4.0006      [illegible]   -136.9660         [illegible]
 JOGB
                        -.15150000E+06 .30300000E+06 -.25804796E+03 .28947930E+03   .70172260E+05    .0
                        -.26243570E+06 -120.0000    -.13147966E+03  -26.1006        -.16854156E+06   .62863939E+06
            JOB
                        -.15367632E+06 .30734113E+06 -.25804796E+03 .28947930E+03   -.75822706E+05
                        -.26616333E+06 -120.0014    .13147966E+03   149.6996        .44403796E+06
 JOGC
                        -.15150000E+06 .30300000E+06 .25094456E+03  .28947930E+03   .75822744E+05    .0
                        .26240571E+06  120.0000     -.14429736E+03  -150.1030       -.61855134E+06   .62863939E+06
            JOC
                        -.15366516E+06 .30734113E+06 .25094456E+03  .28947930E+03   -.75822286E+05
                        .26617833E+06  119.9986     .14429736E+03   29.8996         .44403796E+06
 JOA
                        .30731413E+06 .30734332E+06 .59779948E+00   .31868700E+03   .94584640E+05    .94532494E+03
                        -.17603317E+01 -.0014       .31464033E+03   84.5996         -.48932174E+08   -.48932178E+08
            LMA
                        .32431776E+06 .32431846E+06 .18466194E-38   .18469284E-38   .19751246E-03
                        +.74945432E+03 -.1324       .35585795E-18   2.3899          -.73291156E-05
```

date & time used for plotting purposes

dimensions generated by variable-dimensioning program

Note total length of all labeled common blocks of solution overlays

List of limits, 250 node limit on networks

Input data — branches, switches, sources.

Network Connectivity Table

Local ground

Local ground

$\bar V_k$ Ⓚ Ⓜ $\bar V_m$

$\bar I_{k\to m}$ $\bar I_{m\to k}$

note: $\bar I_{k\to m}$ is the phasor current at end "k", flowing toward "m"

Secondary message printed by Snapshot

Complete steady-state solution printout

$\bar V_{JOGA}$

$\bar V_{JOA}$

$\bar I_{JOGA\to JOA}$

$\bar I_{JOA\to JOGA}$

$P+jQ\big]_{JOGA\to JOA}$

$P+jQ\big]_{JOA\to JOGA}$

Sum of 2 preceding power flows

49c

495

Complete steady-state solution branch-flow printout

Extra, internally-defined node of switched-resistance element

```
JOB
        LNB
JOB
        LNB
JOGA
        JOA
JOGB
        JOB
JOGC
        JOC
LNA
        NLUE
LNB
        ......
```

[illegible]

Steady-state node-injection printout

```
SOLUTION AT NODES WITH KNOWN VOLTAGE.   NODES SHORTED TOGETHER BY SWITCHES ARE SHOWN AS A GROUP OF NAMES, WITH
THE PRINTED RESULT APPLYING TO THE COMPOSITE GROUP.   THE ENTRY 'MVA' IS  SQRT(P**2 + Q**2)  IN UNITS OF POWER,
WHILE  'P.F.'  IS THE ASSOCIATED POWER FACTOR.
               NODE            SOURCE NODE VOLTAGE                 INJECTED SOURCE CURRENT               INJECTED SOURCE POWER
               NAME        RECTANGULAR          POLAR          RECTANGULAR          POLAR              P AND Q      MVA AND P.F.

               JOGA
               JOGB
               JOGC
CARD OF BUS NAMES FOR NODE-VOLTAGE OUTPUT.       LNA    LNB    LNB
CARD OF BUS NAMES FOR NODE-VOLTAGE OUTPUT.       JOA    JOB    JOC
BLANK CARD ENDING NODE NAMES FOR VOLTAGE OUTPUT.
FIRST  5 RESULTS ARE NODE VOLTAGES (TO LOCAL GROUND)
 NEXT  1 RESULTS ARE BRANCH VOLTAGES --- OR POWER CONSUMPTIONS (POWER FLOW IF SWITCH)
FINAL  3 RESULTS ARE BRANCH CURRENTS --- OR ENERGY CONSUMPTIONS (ENERGY FLOW IF SWITCH)
 STEP    TIME       LNA          LNB          JOA          JOB          JOC        LNB          LNB           LNB          JOGC
                                                                                    TERRA        X             TERRA        JOC
                                                              SWITCH 'LNB    ' TO '        ' CLOSED AFTER  0.        SEC.
                                                              SWITCH 'NLUE   ' TO 'LNA     ' CLOSED AFTER  [illegible] SEC.
ENERGY ABSORBED IN SWITCHED RESISTANCE 'LNB    ' TO '        '  [illegible]
                                                              SWITCH 'LNB    ' TO '        ' OPEN AFTER  [illegible] SEC.
                                                              SWITCH 'LNB    ' TO '        ' CLOSED AFTER  [illegible] SEC.
ENERGY ABSORBED IN SWITCHING RESISTANCE 'LNB    ' TO '        '  [illegible]
                                                              SWITCH 'LNB    ' TO '        ' OPEN AFTER  [illegible] SEC.
                                                              SWITCH 'LNB    ' TO '        ' CLOSED AFTER  [illegible] SEC.
ENERGY ABSORBED IN SWITCHED RESISTANCE 'LNB    ' TO '        '  [illegible]
                                                              SWITCH 'LNB    ' TO '        ' OPEN AFTER  [illegible] SEC.
                                                              SWITCH 'LNB    ' TO '        ' CLOSED AFTER  [illegible] SEC.
```

Node voltage output cards are read & listed here.

time in seconds

Node voltages

power

branch current

energy

branch current

```
PEAK OUTPUT VARIABLE VALUES WHICH OCCURRED DURING THE SIMULATION FOLLOW.   A MINUS SIGN MEANS THAT THE PEAK
ABSOLUTE VALUE OCCURRED WITH NEGATIVE POLARITY.   THE ORDER AND COLUMN POSITIONING ARE THE SAME AS FOR THE REGULAR
PRINTED OUTPUT VS. TIME (SEE PRINTED HEADINGS ABOVE).
        .50592E+06 -.37999E+06 -.29939E+06  .31492E+06 -.31491E+06  .12159E+06  .25043E+04  .34199E+06  .10996E+06
```

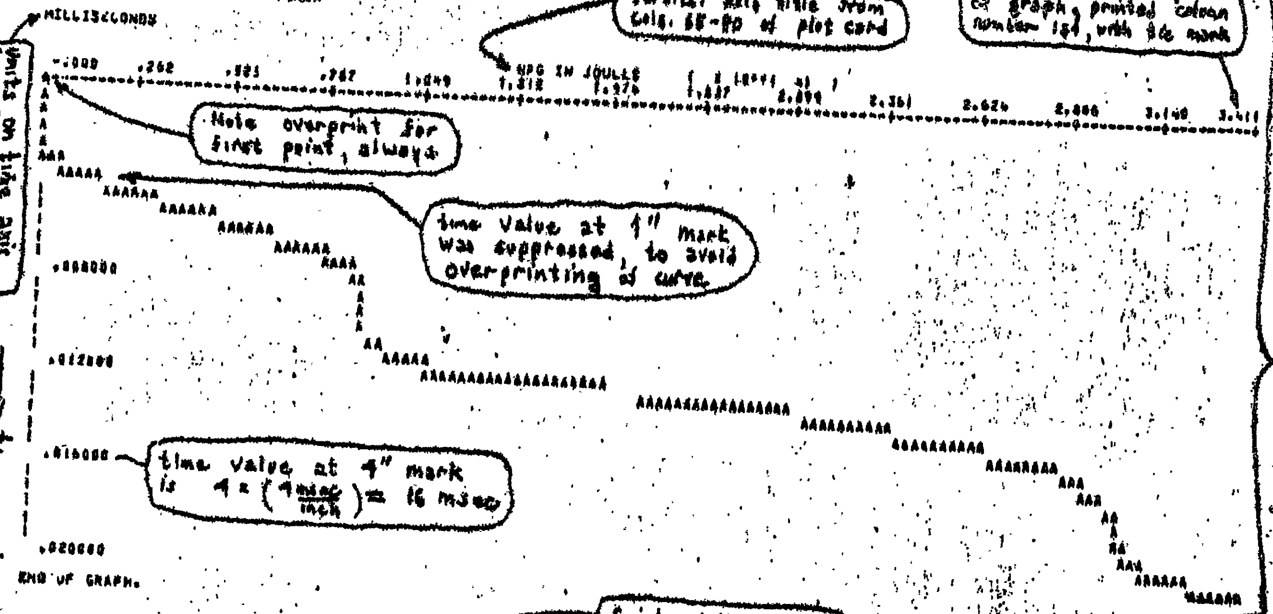
Peak value printout

```
REQUEST FOR DRAWING OF PLOT CHARACTERS.          | PRINT HEAD OFF
PLOT SUBTITLE CARD.                              | 1ST SUBTITLE TEXT CARD, 78 CHARACTERS LONG, LOCAL TO THIS ONE PLOT ONLY.
PLOT SUBTITLE CARD.                              | 2ND SUBTITLE TEXT CARD, ....
REDEFINITION OF SMOOTHING TOLERANCE    .8        |
** PLOT CARD.                                    | 124 2. 0.0 22.          0.0    SMOOTH
PLOT CASE-TITLE TEXT.                            |                         LNS      .MG
REDEFINITION OF SMOOTHING TOLERANCE   .1000E+01  | 78-CHARACTER CASE-TITLE TEXT FOR USER'S MANUAL ILLUSTRATIVE TEST PROBLEM PLOT.
REQUEST FOR CALCOMP AND LINE PRINTER PLOTS.      |                   AED. VOLTS. B-PHVOLTAGE IN VOLTS
REQUEST FOR TYPING OF PLOT CHARACTERS.           | CALCOMP PRINTER  .01    SMOOTH
** PLOT CARD.                                    | PRINT HEAD ON
                                                 | 134 4. 0.0 22.          .MG     SWITCHED-A NRG  NRG IN JOULES
```

Images of cards for plotting

Same meaning as on Calcomp plot

```
                                                  SWITCHED-A NRG
                           78-CHARACTER CASE-TITLE TEXT FOR USER'S MANUAL ILLUSTRATIVE TEST PROBLEM PLOT.
01/02/76  14.49.54     2
PLOT TYPE          9
NODE NAMES       .MG      TEKAA
```



Vertical axis title from cols. 55-80 of plot card

value at extreme right of graph, printed column number 131, with its mark

Note overprint for first point, always

time value at 1" mark was suppressed, to avoid over-printing of curve.

time value at 4" mark is $4 \times \left(4 \frac{\text{msec}}{\text{inch}}\right) = 16$ msec

Units on time axis, time 4" punched in cols. of plot card

time axis

Line printer plot

final plotting card is blank card

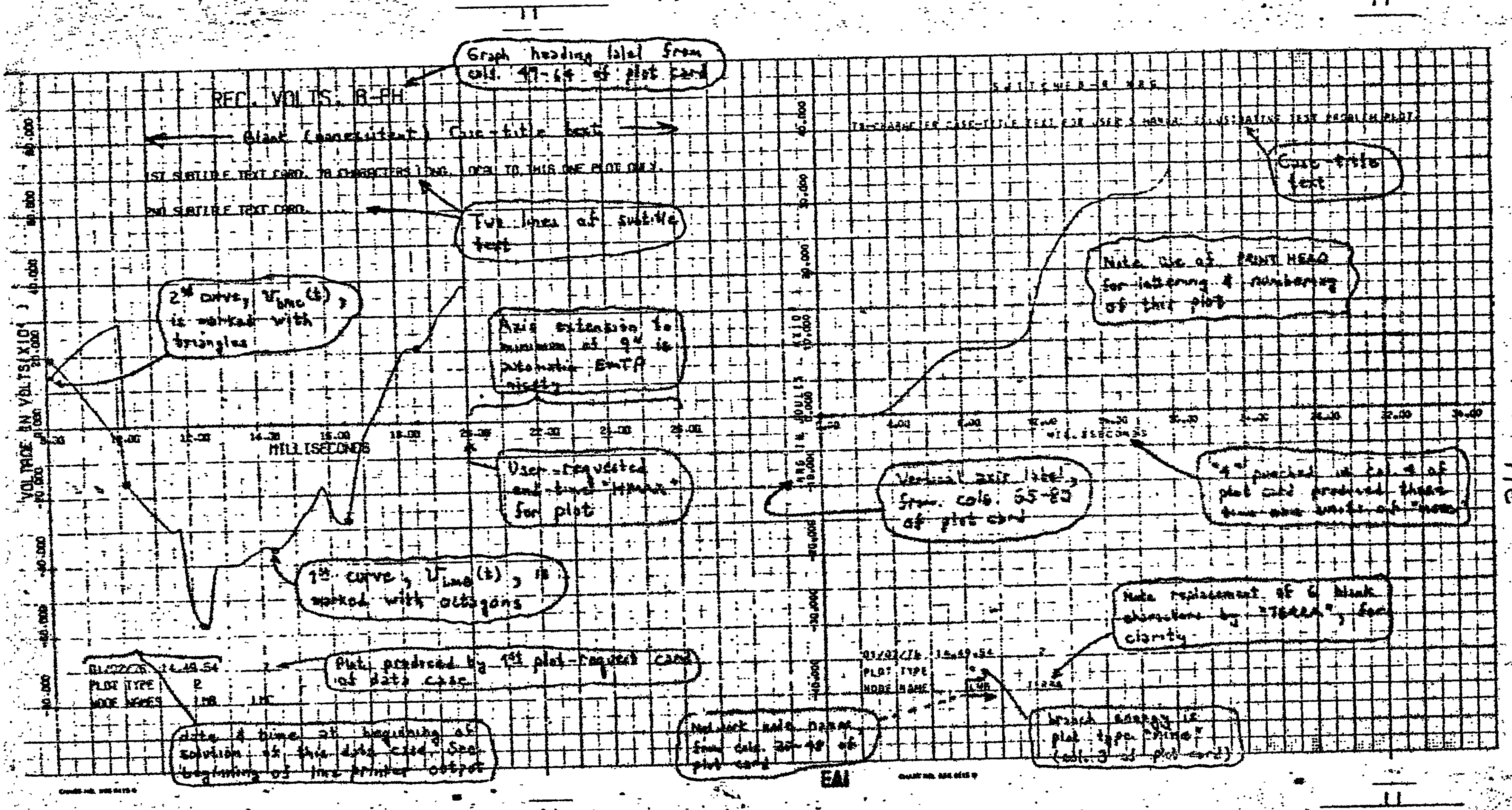
```
BLANK CARD TERMINATING PLOT SPEC. CARDS.

CORE STORAGE FIGURES FOR PRECEDING DATA CASE NOW COMPLETED.
A VALUE OF  -9999 INDICATES DEFAULT, WITH NO FIGURE AVAILABLE.  ---------------------------  PRESENT    PROGRAM
                                                                                               FIGURE     LIMIT (NAME)
    SIZE LIST 1.    NUMBER OF NETWORK NODES.                                                      13       240 (LBUS)
    SIZE LIST 2.    NUMBER OF NETWORK BRANCHES.                                                   12       300 (LBRNCH)
    SIZE LIST 3.    NUMBER OF DATA VALUES IN R, L, C TABLES.                                      17       500 (LDATA)
    SIZE LIST 4.    NUMBER OF ENTRIES IN SOURCE TABLE.                                             5       130 (LEXCT)
    SIZE LIST 5.    MAX NUMBER OF UPPER-TRI FACTORS DURING SOLUTION.                              23      1500 (LYMAT)
    SIZE LIST 6.    NUMBER OF ENTRIES IN SWITCH TABLE.                                             3        40 (LSWTCH)
    SIZE LIST 7.    NUMBER OF NONZERO ENTRIES IN REDUCED MATRIX (YBB/YBB).                        13       500 (LSMAT)
    SIZE LIST 8.    NUMBER OF PAST HISTORY POINTS FOR DISTRIBUTED LINES.                          31      1750 (LPAST)
    SIZE LIST 9.    NUMBER OF NONLINEAR ELEMENTS.                                                  [illegible]        75 (LNONL)
    SIZE LIST 10.   NUMBER OF POINTS DEFINING NONLINEAR CHARACTERISTICS.                           [illegible]        55 (LCHAR)
    SIZE LIST 11.   NUMBER OF BRANCH OR SELECTIVE-NODE-VOLTAGE OUTPUTS.                            [illegible]        60 (NOUT)
    SIZE LIST 12.   NUMBER OF OUTPUT QUANTITIES (LIMITED ONLY WHEN PRINTING MAX ABSOLUTE VALUES).  [illegible]        50 (LPEAK)
    SIZE LIST 13.   NUMBER OF FREQUENCY-DEPENDENT LINES.                                           [illegible]         5 (LFDEP)
    SIZE LIST 14.   NUMBER OF CELLS USED TO STORE FREQ.-DEPENDENCE WEIGHTING FUNCTIONS.            [illegible]       400 (LWT)
    SIZE LIST 15.   NUMBER OF CELLS USED FOR EXPONENTIAL-TAIL LINE-HISTORY STORAGE.                [illegible]        50 (LTAILS)
    SIZE LIST 16.   NUMBER OF SWITCHES BEARING NODE NAME 'FAULT ENTERY'.                           [illegible]         3 (LJUMP)
    SIZE LIST 17.   NUMBER OF DYNAMIC SYNCHRONOUS MACHINES.                                        [illegible]         2 (LSYN)
    SIZE LIST 18.   NUMBER OF BRANCH POWER-AND-ENERGY OUTPUTS.                                     [illegible]         5 (MAXPE)
    SIZE LIST 99.   GIANT ARRAYS FOR RENUMBERING AND STEADY-STATE SOLUTION CALCULATIONS.          30      3112 (IOFGND)
TIMING FIGURES (DECIMAL) CHARACTERIZING CASE SOLUTION SPEED.  --------------------------------  CP SEC    I/O SEC    SUM SEC
    DATA INPUT, SORTING, AND RENUMBERING (PRE STEADY STATE STUFF) .....                           .913      1.360      2.273
    STEADY-STATE (S.S.) SOLUTION CALCULATIONS .....                                               .496      1.288      1.784
    POST-S.S. TO PRE-INTEGRATION-SETUP CALCULATIONS .....                                         .103       .620       .723
    INTEGRATION CALCULATION (TIME IN TIME-STEP LOOP) .....                                       2.015      1.064      3.079
    COMPUTER TIME IN PLOTTING OR STATISTICS TERMINATION OVERLAY .....                            6.952     12.626     19.578
                                                                                      ------------------------------------
                                                                             TOTALS   10.501     16.956     27.457
```

dependent list, a function of the size of /LABEL/ only

Case termination statistics

```
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) = 01/02/76  14.50.38  ANY PLOTS BEAR SAME FIGURES.
ELECTROMAGNETIC TRANSIENTS PROGRAM OF THE BONNEVILLE POWER ADMINISTRATION, PORTLAND, OREGON.
IF IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE 150-PAGE USER'S MANUAL.
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF   /LABEL/   EQUALS   77387   INTEGER WORDS.
  240   300   500   130  1500    40   500  1750    75    55    60    50     5   400    50     3     2     5
-----------------------------------------------------------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA | INPUT DATA CARD IMAGES PRINTED BELOW, 1-80 COLUMNS, CHARACTER BY CHARACTER.
                                                  0         1         2         3         4         5         6         7         8
                                                  0         0         0         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------------------
BLANK TERMINATION-OF-RUN CARD.                    |
```

Note EMTP is shut off with blank card beginning next (nonexistent) case



Graph heading label from cols. 47-64 of plot card

Blank (nonexistent) Case-title text

Two lines of subtitle text

2nd curve, $V_{LMC}(t)$, is marked with triangles

Axis extension to minimum of 9d is automatic EMTP nicety

User-requested end-time "HMAX" for plot

1st curve, $V_{LMB}(t)$, is marked with octagons

Plot produced by 1st plot-request card of data case.

date & time at beginning of solution of this data case. See beginning of line printer output

[illegible] node names from cols. 33-48 of plot card

Case-title text

Note use of PRINT HEAD for lettering & numbering of this plot

Vertical axis label, from cols. 65-83 of plot card

"4" punched in col. 4 of plot card produced these time-axis units of "msec"

Note replacement of 6 blank characters by "TERRA", for clarity

branch energy is plot type "nine" (col. 3 of plot card)

2.4 EMTP Error-Message Terminations

All sorts of user data errors or misunderstandings can produce situations where the EMTP will terminate execution of a data case being solved by means of the printing out of an appropriate error message. A sample is shown below, for which the following points might be made:

a) "KILL CODE NUMBER" is just a characteristic number assigned to the particular error message in question; it has no special significance to the user, as such. Each different error message has such a unique number associated with it.

b) "OVERLAY NUMBER" refers to the overlay number within the UTPF (from which the present EMTP version has been translated) where the error condition has been detected. This localizes the point of trouble to within one of the FORTRAN modules of that overlay:

Number "-1" is for the "main" code (principal module "MAIN00"), which is always in core.

Number "0" is for the first primary level overlay (principal module "MAIN10"), which calls all solution overlays (numbers 1-20).

Positive integers are associated with overlays whose principal modules have names beginning with the four letters "OVER" , and which end with the one or two digits of the overlay number. For example, overlay 13 has principal module "OVER13" .

As generated by E/T translation of the UTPF, the EMTP FORTRAN is ordered from front to back in order of increasing overlay number; this makes it easy to locate the overlay in question.

c) "NEARBY STATEMENT NO." is the statement number of a FORTRAN statement near the point in the code where the error condition was detected. This is useful in tracing down program bugs, when reference to the FORTRAN coding is required. This statement number should always be unique. Having visually located the statement number in question (within a module of the overlay in question), control has then passed through a nearby statement which stores this number in LSTAT(19) . Shortly before or after this, the kill code number should also be assigned, to variable "KILL" .

d) Core-storage figures which follow the error message may not all (or even "any", in extreme cases) be valid. A value of "-9999" will be found wherever the figure in question is not known by the EMTP at this point of the execution where the decision to kill the case has been made.

e) The user will note the "case-recovery" attempt by the EMTP, after the error message and case summary statistics have all been completed. Upon the encounter of a "BEGIN NEW DATA CASE" record, solution would then begin for the following data case (if any). See Section 1.0a .

```
CAUTION. ---- DURING Y-MATRIX ELIMINATION FOR STEADY-STATE SOLUTION VOLTAGES, A NEAR-ZERO DIAGONAL ELEMENT
              FOR NODE '      A' EXISTS JUST BEFORE RECIPROCATION.   USING MAGNITUDES SQUARED FOR ALL 3 QUANTITIES, WE HAVE
              ORIGINAL DIAGONAL VALUE =    .100E+05.   QUESTIONABLE VALUE =    .100E-11.   TOLERANCE RATIO =    .100E-15.
              THE NODE IN QUESTION MAY BE CONNECTED TO OTHER NODES, FORMING A SUBNETWORK.   BUT THE SUBNETWORK HAS NO (OR
              VERY WEAK) PATH TO GROUND OR OTHER KNOWN-VOLTAGE NODE IN THE STEADY-STATE.   SOLUTION VOLTAGES OF THIS
              SUBNETWORK WILL ALL BE SET TO ZERO.

--------------------------------------------------------------------------------------------------------------------------
ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR
ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR
--------------------------------------------------------------------------------------------------------------------------

YOU LOSE, FELLA.   THE T.P. LOGIC HAS DETECTED AN ERROR CONDITION, AND IS GOING TO TERMINATE YOUR RUN.  THE FOLLOWING
PRINTOUT MESSAGE SUMMARIZES THE DATA DIFFICULTY LEADING TO THIS PROGRAM DECISION.   BY STUDYING THIS MESSAGE, THE PROBLEM
DATA, AND THE RULES DELINEATED BY THE 153-PAGE T.P. USERS MANUAL, IT IS HOPED THAT THE USER CAN RECTIFY THE PROBLEM.
IF STILL IN DOUBT AFTER SOME STUDY, COME SEE PROGRAM MAINTENANCE FOR ASSISTANCE.
WHERE AN OTHERWISE-UNIDENTIFIED CARD IS REFERRED TO, OR IS CALLED THE 'LAST' CARD, THIS MEANS THE MOST-RECENTLY-
READ CARD OF THE INPUT DATA DECK.   THE 80-COLUMN CARD IMAGE IN QUESTION IS THE LAST ONE PRINTED OUT BEFORE THIS
TERMINATION MESSAGE.
                KILL CODE NUMBER   ⓐ          OVERLAY NUMBER   ⓑ      NEARBY STATEMENT NO.  ⓒ
                       21                            16                        5046
    NO.   WE CAN NOT VALIDLY SET VOLTAGE OF DISCONNECTED SUBNETWORK LAST IDENTIFIED TO ZERO, SINCE IT APPEARS
    THAT A CURRENT SOURCE FEEDS THIS SUBNETWORK.   FOR THIS CASE, EITHER KIRCHHOFF'S CURRENT LAW FOR THE SUBNETWORK
    IS VIOLATED (CURRENT IN DOES NOT EQUAL CURRENT OUT), OR THE SOLUTION IS INDETERMINATE (SUBNETWORK VOLTAGE SOLUTION
    IS ONLY DETERMINED UP TO AN ARBITRARY CONSTANT).   IN EITHER CASE, THE PROBLEM IS ILL-POSED PHYSICALLY, AND
    MUST BE REJECTED.   USER HAD BETTER RECONSIDER HIS NETWORK IN THE VICINITY OF NODE '      A', TO EITHER REMOVE
    THE SINGULARITY, OR THE CURRENT SOURCE(S), OR BOTH.

CORE STORAGE FIGURES FOR PRECEDING DATA CASE NOW COMPLETED.  ---------------------------------  PRESENT   PROGRAM
A VALUE OF  -9999 INDICATES DEFAULT, WITH NO FIGURE AVAILABLE.                                   FIGURE     LIMIT (NAME)
   SIZE LIST  1.   NUMBER OF NETWORK NODES.                                                          22       249 (LBUS)
   SIZE LIST  2.   NUMBER OF NETWORK BRANCHES.                                                       26       300 (LBRNCH)
   SIZE LIST  3.   NUMBER OF DATA VALUES IN R, L, C TABLES.                                          16       500 (LDATA)
   SIZE LIST  4.   NUMBER OF ENTRIES IN SOURCE TABLE.                                                 3       100 (LEXCT)
   SIZE LIST  5.   MAX NUMBER OF UPPER-TRI FACTORS DURING SOLUTION.                               -9999      1500 (LYMAT)
   SIZE LIST  6.   NUMBER OF ENTRIES IN SWITCH TABLE.                                                 7        40 (LSWTCH)
   SIZE LIST  7.   NUMBER OF NONZERO ENTRIES IN REDUCED MATRIX (YB ##SC).                        -9999       500 (LSMAT)
   SIZE LIST  8.   NUMBER OF PAST HISTORY POINTS FOR DISTRIBUTED LINES.                          -9999      4750 (LPAST)
   SIZE LIST  9.   NUMBER OF NONLINEAR ELEMENTS.                                         ⓓ            0        75 (LNONL)
   SIZE LIST 10.   NUMBER OF POINTS DEFINING NONLINEAR CHARACTERISTICS.                               0        55 (LCHAR)
   SIZE LIST 11.   NUMBER OF BRANCH OR SELECTIVE-NODE-VOLTAGE OUTPUTS.                           -9999        50 (NOUT)
   SIZE LIST 12.   NUMBER OF OUTPUT QUANTITIES (LIMITED ONLY WHEN PRINTING MAX ABSOLUTE VALUES).  +9999        50 (LPEAK)
   SIZE LIST 13.   NUMBER OF FREQUENCY-DEPENDENT LINES.                                               0         5 (LFDEP)
   SIZE LIST 14.   NUMBER OF CELLS USED TO STORE FREQ.-DEPENDENCE WEIGHTING FUNCTIONS.                0       400 (LWT)
   SIZE LIST 15.   NUMBER OF CELLS USED FOR EXPONENTIAL-TAIL LINE-HISTORY STORAGE.               -9999        50 (LTAILS)
   SIZE LIST 16.   NUMBER OF SWITCHES BEARING CODE NAME 'PART ENTE.'.                                 0         3 (LJUMP)
   SIZE LIST 17.   NUMBER OF DYNAMIC SYNCHRONOUS MACHINES.                                            0         2 (LSYN)
   SIZE LIST 18.   NUMBER OF BRANCH POWER-AND-ENERGY OUTPUTS.                                         0         5 (MAXPE)
   SIZE LIST 99.   GIANT ARRAYS FOR RENUMBERING AND STEADY-STATE SOLUTION CALCULATIONS.              36      3112 (IDFGMD)

--------------------------------------------------------------------------------------------------------------------------
ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR
ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR/ERROR
--------------------------------------------------------------------------------------------------------------------------
CARD IGNORED IN SEARCH FOR NEW-CASE BEGINNING.   |     A2    B2    C2              A4    B4    C4
CARD IGNORED IN SEARCH FOR NEW-CASE BEGINNING.   |  ⓔ
CARD IGNORED IN SEARCH FOR NEW-CASE BEGINNING.   |
CARD IGNORED IN SEARCH FOR NEW-CASE BEGINNING.   |
CARD IGNORED IN SEARCH FOR NEW-CASE BEGINNING.   |
CARD IGNORED IN SEARCH FOR NEW-CASE BEGINNING.   |                SOURCE VOLTAGE
CARD IGNORED IN SEARCH FOR NEW-CASE BEGINNING.   | 134100    01.00-20002000     A2     B2     C2           SOURCE        VOLTAGE
CARD IGNORED IN SEARCH FOR NEW-CASE BEGINNING.   | 134100    01.00-20002000     A4     B4     C4         P T  VOLTAGE    VOLTAGE
CARD IGNORED IN SEARCH FOR NEW-CASE BEGINNING.   |                BRANCH CURRENTS
```

⋮ Etc.   ⋮ Etc.

4. FORMULAS

The theory behind the TRANSIENTS program is explained in references 1-2 of Sect. 0.4 . Some points will be explained in more detail here.

4.1 TRANSFORMATION USED FOR MULTIPHASE LINES

Multiphase lines with distributed parameters are assumed to be " balanced". This shall be defined as follows: The self-impedances (capacitances) of all phases are equal among themselves and all mutual impedances (capacitances) are equal among themselves. Thus, the series inductance matrix of a balanced line in the phase domain is

$$\left[L_{phase}\right] = \begin{bmatrix} L_s & L_m & L_m & \dots L_m \\ L_m & L_s & L_m & \dots L_m \\ L_m & L_m & L_s & \dots L_m \\ \cdot & \cdot & \cdot & \cdot\cdot\cdot\cdot\cdot\cdot \\ L_m & L_m & L_m & \dots L_s \end{bmatrix} \quad \text{with} \begin{cases} L_s = \text{self inductance} \\ L_m = \text{mutual inductance} \end{cases}$$

and analogous for $\left[C_{phase}\right]$.

The voltage drop along the series inductance is

$$-\left[\frac{\partial e_{phase}}{\partial t}\right] = \left[L_{phase}\right]\left[i_{phase}\right]. \qquad (1)$$

In eq. (1), all phases are coupled . In the TRANSIENTS program, phase quantities are transformed to mode quantities such that

$$-\left[\frac{\partial e_{mode}}{\partial t}\right] = \left[L_{mode}\right]\left[i_{mode}\right] \qquad (2)$$

has a diagonal matrix $\left[L_{mode}\right]$. This means that the mode quantities become decoupled.

The transformation being used is due to H. Karrenbauer (see no. 15 in the list of references given in Ref. 1 . It has certain advantages, among them:

(a) the transformation matrices are real,

(b) they are identical for voltages and currents,

(c) they are very convenient from a programming standpoint (they are valid for any number of phases so that only one general formula is necessary for any number of phases).

The transformation works only for "balanced" lines, where incidentally, it is still valid even if the line parameters are frequency-dependent.

It is defined by

$$[e_{phase}] = [T]\cdot[e_{mode}] \tag{3a}$$

$$[i_{phase}] = [T]\cdot[i_{mode}]$$

$$\text{with } [T] = \begin{bmatrix} 1 & 1 & 1 & \ldots 1 \\ 1 & 1-M & 1 & \ldots 1 \\ 1 & 1 & 1-M & \ldots 1 \\ \cdot & \cdot & \cdot & \cdot \\ 1 & 1 & 1 & \ldots 1-M \end{bmatrix} \text{, with } M = \text{number of phases} \tag{3b}$$

The inverse transformation,

$$[e_{mode}] = [T]^{-1}[e_{phase}] \text{ , identical for current ,} \tag{4a}$$

has the matrix

$$[T]^{-1} = \frac{1}{M}\left[\begin{array}{c|cccc} 1 & 1 & 1 & \ldots & 1 \\ \hline 1 & -1 & & & \\ 1 & & -1 & & \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & & & & -1 \end{array}\right] \tag{4b}$$

} all elements are "1" in first row

all elements are "1" in first column

"-1" in diagonal and zeros outside diagonal

Physical meaning of mode quantities: From (4b) it can be seen that the first mode describes the loop with all conductors in parallel and return through the ground (identical to zero sequence) and the second, ..., M-th mode describes the loop consisting of the 1st conductor and return via the second, ..., M-th conductor, respectively.

Matrices in mode quantities. The series impedance matrix in mode quantities is

$$[Z_{mode}] = [T]^{-1}[Z_{phase}][T] = \begin{bmatrix} Z_0 & & & & \\ & Z_1 & & & \\ & & Z_1 & & \\ & & & \ddots & \\ & & & & Z_1 \end{bmatrix} \tag{5a}$$

$$\left.\begin{aligned} \text{with } Z_0 &= Z_s + (M-1)Z_m \\ Z_1 &= Z_s - Z_m \end{aligned}\right\} \tag{5b}$$

$$\left.\begin{aligned} \text{and vice versa}\quad Z_s &= \frac{1}{M}\left[Z_0 + (M-1)Z_1\right] \\ Z_m &= \frac{1}{M}\left(Z_0 - Z_1\right), \end{aligned}\right\} \tag{5c}$$

where Z_s = self impedance
Z_m = mutual impedance
M = number of phases,

The same equations hold for the capacitance matrices,

$$C_0 = C_s + (M-1)\cdot C_m, \text{ etc.}$$

4.2 LUMPED SERIES RESISTANCE IN LINE

To approximate losses in the lossless line representation, the TRANSIENTS program lumps R/4 at both ends and R/2 at the middle of the line (except when line is assumed to be distortionless), where

$$R = R' \cdot \ell \qquad (6)$$

with R' = resistance per unit length
ℓ = length of line.

A justification for lumping the series resistance was given by C. Boonyubol and C. Calabrese, "Equivalent distributed-parameter simulation for transient study of a transmission line". Conference paper, IEEE Summer Power Meeting, Chicago, June 1968. The authors lump the resistance at the sending end; it is computed from

$$R_{equivalent} = Z \cdot \tanh\left(\frac{R'\ell}{Z}\right), \qquad (7)$$

where Z = surge impedance.

The line is then treated as lossless as in the TRANSIENTS program.

Obviously, R from (6) and $R_{equivalent}$ from (7) are not identical. Since $R'\ell \ll Z$, one can develop the hyperbolic tangent into a series,

$$\tanh\left(\frac{R'\ell}{Z}\right) = \frac{R'\ell}{Z} - \frac{1}{3}\left(\frac{R'\ell}{Z}\right)^3 + \frac{2}{15}\left(\frac{R'\ell}{Z}\right)^5 \pm \ldots$$

If only the first term is retained in the series, then

$$R_{equivalent} \approx R'\ell .$$

Therefore, $R_{equivalent}$ is approximately the same as R from (6).

If $Z = 330\,\Omega$ and $R'\ell = 12\,\Omega$ (typical values*), then

$$\tanh\left(\frac{R'\ell}{Z}\right) = 0.0364 - 0.000016 \pm \ldots$$

The error by neglecting the third-order and higher terms is about 0.04%, which is extremely small.

---

[*] These are typical values for the positive-sequence mode, but not necessarily representative of the zero sequence, particularly at higher frequencies. Therefore caution must be exercised in lumping the resistance should $R'\ell$ no longer be small compared with Z. Of course exact representation of the zero sequence mode is now possible using the frequency-dependence option (see Section 1.27).

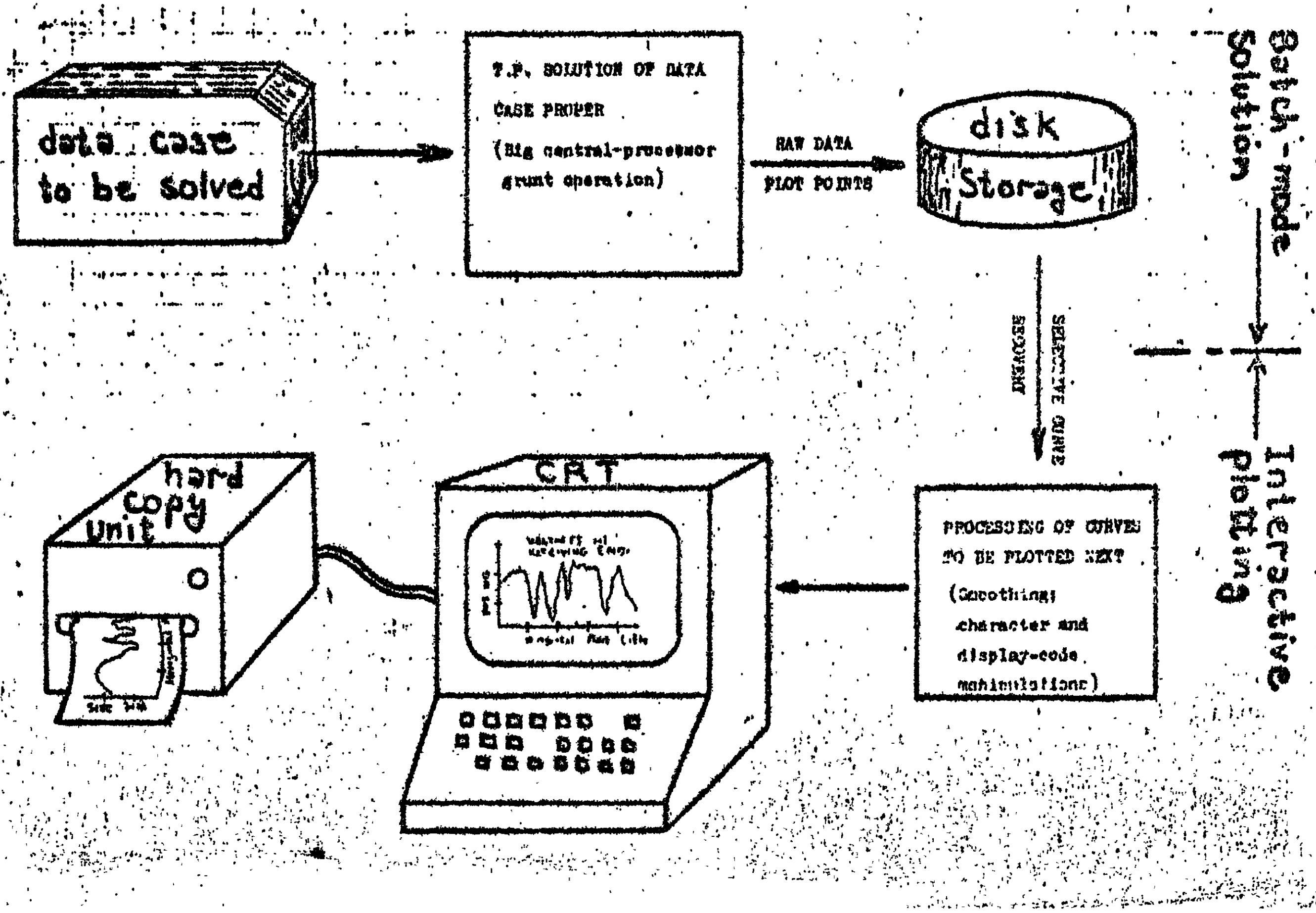
5.0 INTERACTIVE CRT PLOTTING OF EMTP SOLUTIONS

Let's begin by making it clear what this section is not about. Requests for graphs of EMTP output variables can be included along with the data case which defines and solves the problem of int.rest (see Section 1.10). Or, such plot requests can be split off into a separate follow-up "REPLOT" job (see Section 1.0d). Either way, this is batch-mode EMTP plotting, which is not what now concerns us.

5.0A Interactive CRT Plotting

More powerful, efficient, and flexible is interactive CRT plotting of EMTP output variables. As with the "REPLOT" option, the plotting of a previously-solved EMTP data case is involved. But rather than submit the plot requests as a pre-defined job, here the user sits down before a vector-graphic CRT terminal and does his plotting in real time. Attributes of such interactiv CRT plotting include the following:

* Speed. A graph is produced in seconds. Then too, one is not slowed down by a backlog on the conventional plotter (which may be hours, typically).
* Data errors are no problem, since they are discovered experimentally and can be corrected in seconds.
* The user is not required to know ahead of time what he should be looking for or at. A survey of problem performance can be made experimentally, by trial and error, learning as one looks.
* The time scaling can be experimentally adjusted by eye so as to produce pleasing results which properly display the phenomena of interest.
* If the user likes what he sees on the screen, a hard copy unit can produce a paper copy in seconds. One also can dispatch plots to the pen-and-ink plotter (although these might not be available for hours, remember).


data case to be solved
T.P. SOLUTION OF DATA CASE PROPER
(Big central-processor grunt operation)
RAW DATA
PLOT POINTS
disk Storage
SELECTIVE CURVE
Batch-mode Solution
Interactive plotting
PROCESSING OF CURVES TO BE PLOTTED NEXT
(Smoothing; character and display-code manipulations)
CRT
hard copy unit

So much for the summary description. Interactive CRT plotting of EMTP results is more fully described in two EMTP memoranda of Ref. 8, Vol. II. The 10-page memo dated November 25, 1974 describes the concept, and shows samples of hard-copy output; that dated January 25, 1975 provides 13 pages of user instructions for the interactive CRT plotting procedure as used at BPA. There have been a few extensions and refinements made since then, but the basic concept and format remains intact. As of July, 1977, the BPA interactive CRT plotting program is tied to both a Control Data 6000-Series computer, and also to a Tektronix CRT terminal. The program is small (perhaps 1000 FORTRAN cards), but is both machine and screen-dependent.

Interactive CRT plotting has been a tremendous success with EMTP users at BPA, with perhaps 95% of all EMTP plotting now being done by this means. It is only for published papers or final reports that the pen-and-ink plotter continues to enjoy regular EMTP patronage.

Then in February of 1979, BPA bought a DEC VAX-11/780 computer system (see Section 0.5h), and all EMTP usage was switched from CDC to this system. The interactive plotting program was then enhanced at that time (see 28-page memo of Ref. 8, Vol. IX, 11 May 1979, pagination PIEP), and is now about 2400 cards in size. It should work successfully with any Tektronix vector-graphic terminal which can be driven by the user's Tektronix PLOT10 plotting package (proprietary with Tektronix, though priced very reasonably; most users of a Tektronix terminal already have this). At BPA we still just drive a big-screen (19-inch) 4014 , while Ned in Minneapolis (see Section 0.5a) plots remotely on a cheap, small-screen 4006 via a 300 baud telephone connection to our VAX. The optional COPY command of interactive plotting will dispatch a copy of what is on the screen to the system plotter only if the user also has a CalComp plotting interface (subroutines "LINE" , "SYMBOL" , "AXIS" , etc.).

It is hoped that the BPA VAX interactive plotting program may soon be available for execution on other computer systems. The most important of these is IBM, of course. Mike Price of AEP was interested in converting the package for use on the AEP IBM 3033 , so it was sent to him on tape the morning of March 13th, 1980. Whether this might be available when new EMTP versions are distributed during the summer of 1980 can not be predicted at this time (late April, 1980). If an IBM user is interested, all he can do is inquire at the time. See Section 0.5b for Mike Price's telephone number.

5.00 Format of EMTP Plot Data Points on "LUNIT4"

The EMTP writes output variables on logical unit number "LUNIT4" during the solution process (in the time-step loop of overlay number 16). Before entering the time-step loop (in overlay 15), either two or three records of header information are first outputted. It is the precise format of this "LUNIT4" file which shall now be described. For a conventional (not TACS-only) data case:

First Record:

DATE1(2) ——— 8-character BCD specification of the date that the solution wa generated. It is to be printed out as 2A4 information, hich might then look like "10/26/74" . Two EMTP "ALPHANUMERIC" words are involved, the mode and/or length of which is machine dependent. See Program Maintenance for details.

TCLOCK(2) ——— 8-character BCD specification of the wall-clock time at which the solution was begun. It is to be printed out using 2A4 format, producing a result looking something like "13.42.07". Two EMTP "ALPHANUMERIC" words are involved, the mode and/or length of which is machine dependent. See Program Maintenance for details.

NTOT ——— The number of A6 alphanumeric names which constitute the end of this first record. For EMTP usage, this is the number of problem nodes.

NUMNVO ——— The number of type-1 plot variables in the plot file. For EMTP usage, this is the number of node voltage outputs of the case in question.

NUMBCO ——— The number of type-9 plot variables in the plot file. For EMTP usage, this is the number of branch-current outputs.

NC ——— The number of type-8 and type-9 plot variables in the plot file. For EMTP usage, this is the total number of branch outputs for the solution in question, both branch currents and branch voltages.

(BUS(I), I=1, NTOT) ——— A6 alphanumeric names by which plot variables are identified. For EMTP usage, this is the complete list of network node names (including ground, which is node number 1, having 6 blank characters for its name). A vector of EMTP "ALPHANUMERIC" words is involved, the mode and/or length of which is machine dependent. See Program Maintenance for details.

The term "ALPHANUMERIC" might be documented further (see definition of DATE1, TCLOCK, and BUS). By definition, such variables are used to store A6 information (e.g., node names). For conventional byte-organized machines like IBM, PRIME, VAX, and SEL, such variables are of type REAL*8 . For most word machines like CDC and Honeywell, they are of type INTEGER .

Next Record (#2, if it exists)

If parameter NUMNVO as read from record number 1 is positive, then the second record of header information contains integer numbers which identify each type-1 plot variable in the data file:

(IBSOUT(I), I=1, NUMNVO)

To find the A6 name of the corresponding type-1 variables in the output file, these integers are used as subscripts of array BUS .

For EMTP usage, K = IBSOUT(I) is the node number of the I-th node-voltage output quantity. The 6-character node name is BUS(K) .

Should NUMNVO be zero, the aforementioned record is nonexistent.

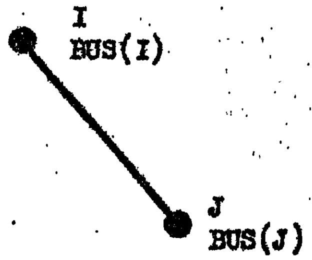
Final Header Record (if it exists)

If parameter NC as read from record number 1 is positive, the next record to be read specifies integer numbers identifying type-8 and type-9 plot variables within the plot data file. This record has contents:

(IBRNCH(L), L=1, NC), (JBRNCH(L), L=1, NC)

Both type-8 and type-9 output variables are identified by a pair of alphanumeric (actually BCD; A6 format, in any case) names. Corresponding integers from the two listed arrays are used as subscripts to array BUS in order to obtain the pair of identifying names.

For EMTP usage, I = IBRNCH(L) and J = JBRNCH(L) are the terminal node numbers corresponding to the L-th output branch quantities. The 6-character node names of the ends of the branch in question then are BUS(I) and BUS(J) .



If NC should be zero, the just-mentioned record is nonexistent.

Records Containing Actual Data Points of Output Variables

The preceding header records (two or three in number) are followed by records which specify the numerical plot coordinates of all output variables. A separate record exists for each time-point t_i , containing not only the time value, but also the corresponding numerical value of all output variables:

T, (VOLTI(L), L=1, NUMOUT) NC + NUMNVO

where

T ———— the time in seconds at which all output quantities of this record correspond.

VOLTI(L) ——— The numerical value for the L-th output quantity, at time T . Within this output vector, all type-1 variables (if any) come first, followed by all type-8 variables (if any), followed by all type-9 variables (if any).

These records must occur in order of monotone-increasing time T .

The termination of plot data points is indicated by a record such as the above, having time coordinate set to T = -9999. This is just a convenient termination flag.

For EMTP usage, of course type-1 variables are node voltages, type-8 variables are branch voltages (or powers), and type-9 variables are branch currents (or energies). Thus the stated ordering says simply that node voltages come first, then branch voltages (or powers), and finally branch currents (or energies). Recall that TACS variables and dynamic synchronous machine variables are treated just like they were branch currents, as far as plotting is concerned (i.e., they too are type-9 variables). The same is true of the universal machine (U.M.) variables (also type-9 plotting).

As for the TACS-only stand-alone case, the header records have a little different form. The First Header Record is altered in that (see end of "TACS1A" definition):

a) NTOT and NUMNVO are replaced by IOUTCS , which is the number of TACS output quantities.

b) NUMBCO and NC are given values of zero, always, which means that there are no branch outputs (Type-8 or Type-9 variables).

c) BUS(I) node names are replaced by the vector of TACS output variable names, (ALNOUT(I), I=NDX1, NDX2) .

The Second Header Record simply consists of the ordered positive integers 1, 2, ... , IOUTCS . Finally, there is no Third Header Record.

6. TRANSFORMER REPRESENTATION USING [R] & [L] MATRICES

Type 51, 52, 53 EMTP branch components of Sect. 1.24 can be used for the representation of transformers, excluding nonlinearities.

6.1 Simplified model, with resistance neglected

The cascade connection of a generator and transformer (Fig. 1) can be represented very simply by a voltage source behind a single 3-phase reactance matrix between nodes S and A, if the following conditions are met:

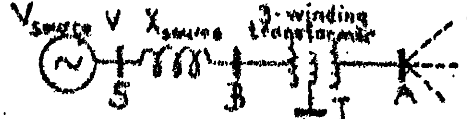


Fig 1. Cascade connection of generator and transformer.

1) The voltage source is balanced,
2) the impedances between S and A are balanced (specifically, no switching is allowed between S and A),
3) in case of a three-winding transformer, the tertiary winding is either unloaded or has balanced reactances as load,
4) no generator currents or currents in tertiary windings are desired (only current from rest of network into A will be correct),
5) the frequencies in the transient phenomena are not too high (see p. 90).

Modeling Technique:

Assume the following data is given:

$X_{source} = 4.811\,\Omega$ (subtransient reactance)

$V_{source} = 380$ kV phase-to-phase

2 three-winding transformers connected in parallel, each rated 2000 MVA, with:

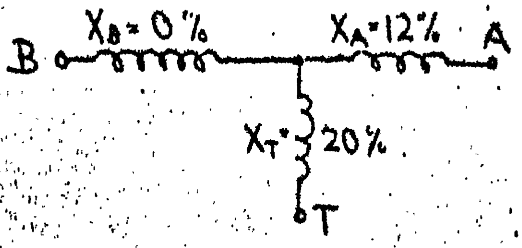
$$\left.\begin{array}{ll} X_{A-B} & = 12\% \\ X_{A-T} & = 32\% \\ X_{B-T} & = 20\% \end{array}\right\} \text{based on 2000 MVA}$$

voltage rating on B-side: 380 kV
voltage rating on A-side: 1050 kV } autotransformer connection with grounded neutral
tertiary connected in delta

First, transform source reactance to side A:

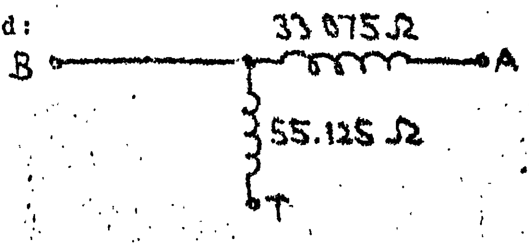
$$X_{source-A} = 4.811\left(\frac{1050}{380}\right)^2 = 36.75\,\Omega$$

Next, set up well-known equivalent circuit for three-winding transformer with all values referred to side A:



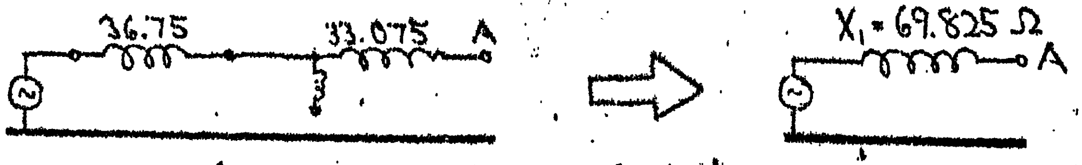
$$\left.\begin{array}{l} X_A = \frac{1}{2}(X_{A-B} + X_{A-T} - X_{B-T}) \\ X_B = \frac{1}{2}(X_{A-B} + X_{B-T} - X_{A-T}) \\ X_T = \frac{1}{2}(X_{A-T} + X_{B-T} - X_{A-B}) \end{array}\right\} \text{only correct if all } X_{ik} \text{ are based on same MVA.}$$

Converted to ohms seen from side A, and 2 transformers paralleled:

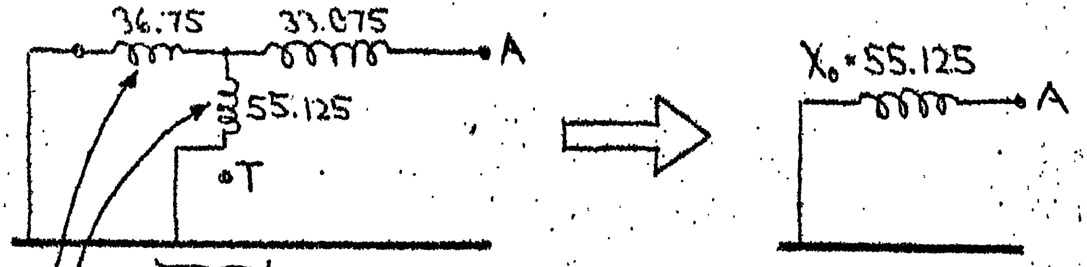


Next, set up the positive sequence and zero sequence networks and combine the reactances.

Positive sequence:



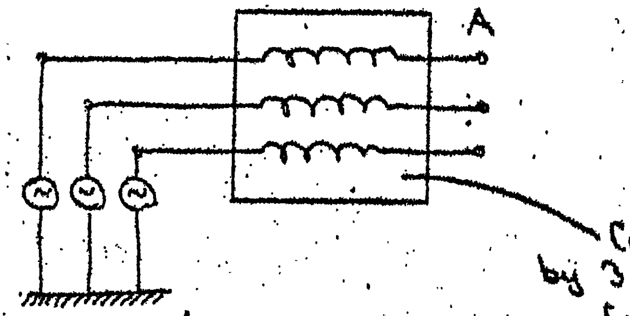
Zero sequence (tertiary in delta and unloaded):



Tertiary node T is isolated, reactance of T-leg is grounded.

2 values in parallel = 22.05 Ω

Finally, transform sequence quantities to phase quantities and represent as follows:



voltage source referred to side A, e.g., $\frac{1050\sqrt{2}}{\sqrt{3}}$ kV peak value (phase to ground) in this example.

Coupled inductances represented by 3·3 matrix

$$[X_{phase}] = \begin{bmatrix} X_s & X_m & X_m \\ X_m & X_s & X_m \\ X_m & X_m & X_s \end{bmatrix}$$

with:
self reactance $X_s = \frac{1}{3}(X_0 + 2X_1)$,
mutual reactance $X_m = \frac{1}{3}(X_0 - X_1)$.

(In example, X_s = 64.925 Ω, X_m = −4.9 Ω).

6.2 More detailed model for single-phase units

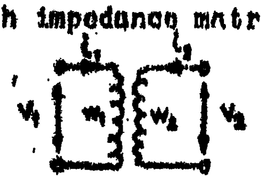
The model described in 6.1 is often inadequate, e.g., for cases with low voltage side switching, with faults on the tertiary side etc. In such cases a more detailed model should be used. The one described here is more detailed in that sense, but it is still approximate and only valid if

1) the frequencies in the transients are not too high, and
2) three-phase banks consist of single-phase units.

A similar model could also be developed for three-phase units by transforming the equations of the equivalent circuits in the positive, negative and zero sequence (including phase shifts) to equations in phase quantities.

6.21 Basic Approach

A single-phase two-winding transformer can be treated as two inductively coupled branches with a branch impedance matrix $[Z] = [R] + j\omega[L]$.



Then the transformer is described by the equation

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = [R]\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + [L]\begin{bmatrix} di_1/dt \\ di_2/dt \end{bmatrix} \qquad (1)$$

The impedance matrix $[R] + j\omega[L]$ is the inverse of the well-known admittance matrix which is used in steady state studies,

$$[Y] = [Z]^{-1} = \left[\begin{array}{c|c} (Y_\ell + \frac{1}{2} Y_m) & -kY_\ell \\ \hline -kY_\ell & k^2 \cdot (Y_\ell + \frac{1}{2} Y_m) \end{array}\right] \qquad (2)$$

with

$k = \frac{W_1}{W_2}$ = transformer ratio

$\omega L_\ell = 1/Y_\ell$ = leakage impedance seen from side 1,

$\omega L_m = 1/Y_m$ = magnetising impedance seen from side 1.

The "XFORMER" supporting routine which is described in Section 7.1 obtains the impedance matrix by inverting the matrix $[Y]$ of Eq. (2). Of course this works only if $[Y]$ is not singular, which means that the magnetizing admittance Y_m must not be zero. The resulting impedance matrix can be used directly in the EMTP for representation of a transformer, without any modification; matrices $[R]$ and $[L]$ are to be punched on branch cards of Type 51, 52, etc. (see Section 1.24).

If the magnetizing admittance is ignored, as is often done in steady-state studies, then $[R] + j\omega[L]$ is infinite and only its inverse

$$\left[[R] + j\omega[L]\right]^{-1}$$

exists. By ignoring the resistance, Eq. (1) can be re-written as

$$\left[L\right]^{-1}\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \frac{d}{dt}\begin{bmatrix} i_1 \\ i_2 \end{bmatrix}, \qquad (3)$$

Eq. (3) could also be used in the TRANSIENTS PROGRAM, but it would require some modifications. This approach was described by W. E. Feero, J. A. Juves and R. W. Long, "Circuit breaker and transformer models for the solution of wavy propagation in distributed-parameter systems," IEEE Trans., Vol. PAS-90, May/June 1971, pp. 1000-1006. I do not know how the resistances could or should be re-introduced in this approach.

For 2-winding transformers, current thinking at BPA is that the user should always use the saturable transformer component of Section 1.25 , rather than the impedance matrices of the present section. Writing of the present section predates development of the "TRANSFORMER" component, which in addition provides for a built-in nonlinearity. Yet, for some 3-winding configurations, several people have observed problems of instability with the "TRANSFORMER" component —— as evidenced by the exponential growth of "noise", which eventually produces an overflow bomboff by the system. Until this enigmatic complication is understood and fully controlled, the use of $[R]$ and $[L]$ matrices for transformer representation will continue to have a place, it is felt. Also, for four or more windings, Hermann has pointed out that the "TRANSFORMER" representation is not as general in some ways, and hence not equivalent.

Scott Meyer, Feb. 1977

6.22. Validity of transformer models obtained using "XFORMER"

Representing 2- and 3-winding transformers as coupled impedances in the form of impedance matrices is valid as long as the capacitances between windings, from windings to the tank and core and between layers of windings can be ignored. This is permissible for moderate frequencies in the transient phenomena (I guess the models are o.k. up to about 2-5 kHz, but this guess should be substantiated by experts on transformers). The model is probably accurate enough for switching surge studies. It is not adequate for lightning surge studies and it may be questionable for recovery voltage studies. Maybe the model can be improved for such cases by adding capacitances (some capacitance data is available from the test reports), but this requires further investigation. The inadequacy for very high frequencies is obvious because the capacitances determine the behavior of the transformer at very high frequencies since the capacitive impedances $1/\omega C$ become very low and the inductive impedances ωL become very high (and, therefore, negligible).

The model from "XFORMER" has one further limitation: It is only valid for single-phase transformers, including three-phase banks made up of single phase units. In general, the model is not correct for three-phase units, especially if the zero sequence short-circuit input impedance differs from the positive sequence short-circuit input impedance, as in core-form construction. For shell-form construction the model may be adequate for three-phase units, but this requires further investigation. The user is advised to always consult someone who has had experience with EMTP transformer modeling, should he have questions.

6.23 Accuracy check on impedance matrix derived by "XFORMER"

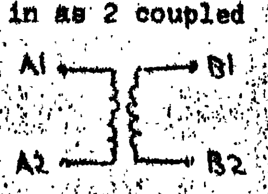
Since the magnetizing impedance is very large compared to the short-circuit input impedance, there is always a danger that the short-circuit input impedance gets lost in the values of the impedance matrix. Such cases will be terminated with an error message:

```
SINGLE-PHASE 3-WINDING TRANSFORMER. IMAGN =-0.00000 PERCENT BASED ON 300MVA
VOLTAGE ACROSS WINDING                       LOSSES   IMPEDANCE BASED ON
      (KV)                                    (KW)    (PER CENT)  (MVA)
HIGH    303.00         HIGH    TO MEDIUM      0.00      9.4600    300.000
MEDIUM  139.60         HIGH    TO LOW         0.00     42.3600    300.000
LOW      34.50         MEDIUM  TO LOW         0.00     31.8400    300.000

ADMITTANCE MATRIX TOO CLOSE TO SINGULAR TO BE INVERTIBLE
```

For further questions, consult Program Maintenance. Also, consider the representation of Section 1.25 ("TRANSFORMER"), for which singularity is no complication. With the saturable transformer component, an infinite magnetizing impedance is perfectly acceptable.

6.24 How to use the model in the TRANSIENTS PROGRAM

A single-phase 2-winding transformer must be read in as 2 coupled branches (first branch A1 to A2, second branch B1 to B2) with the branch having type-codes 51 and 52 (see Section 1.24). There will be three resistance and three inductance (or reactance) values to be punched, since only the lower triangle of [R] and [L] are required.



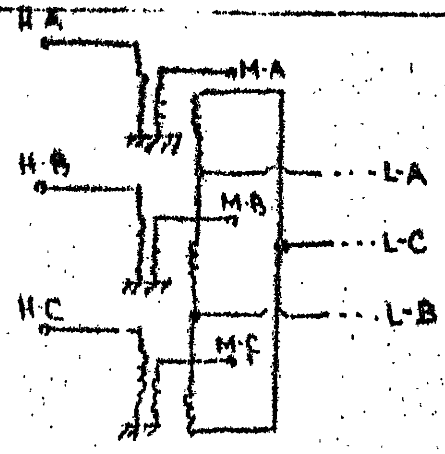
```
51 H-A                                  99972.154
52 M-A                                  46050.638          21218.663
53 L-C   L-A                            11376.889          5242.1922       1296.3764
51 H-B          H-A
52 M-B
53 L-A   L-B
51 H-C          H-A
52 M-C
53 L-B   L-C
```

data identical to first transformer

```
IMPEDANCE MATRIX AS REQUIRED FOR TRANSIENTS PROGRAM (X AT POWER FREQUENCY)
              R                 X                    R                 X                 R                 X
HIGH    -0.               9.9972154E+04
MEDIUM   0.               4.6050638E+04    0.               2.1218663E+04
LOW      0.               1.1376889E+04    0.               5.2421922E+03    0.               1.2963764E+03
```

A single-phase 3-winding transformer must be read as 3 coupled branches with the same branch type.

Example for a three-winding transformer (original data given on p. 97).



Note that it is assumed that inductances are read in the form of reactances ωL at 60 Hz. If inductances are read in mH, then the values ωL should be divided by ω with high accuracy to assure that the short-circuit input impedance is not altered too much (remember that this impedance is very small compared to X_{11}, X_{21}, X_{22}, etc.!).

The impedance matrix obtained with this program is in physical units (Ω) and not in per unit. The correct turns-ratio is assured.

To my knowledge, all users specify the network parameters (resistance, inductance, capacitance) in physical units. It is best to specify voltage and current sources in physical units also to avoid confusions, especially when nonlinear inductances are included with their ψ-i characteristics. Example: For a three-phase transformer bank, made up of single-phase wye-wye-delta transformers with turns ratio $230/\sqrt{3}$ - $115/\sqrt{3}$ - 32 kV, I would specify a source on the 230 kV side as

$$v_A = 188000 \sin(\omega t + \phi) \text{ volts}$$

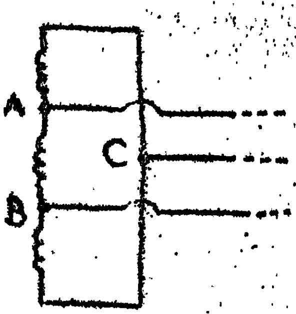
$$v_B = 188000 \sin(\omega t + \phi - 120°) \text{ volts}$$

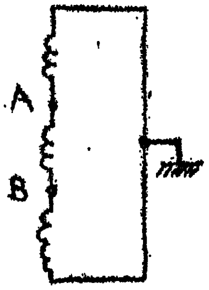
$$v_C = 188000 \sin(\omega t + \phi - 240°) \text{ volts}$$

The transformer would then produce the correct peak voltage to ground of $115\sqrt{2}/\sqrt{3}$ kV on the 115 kv side and of $32\sqrt{2}/\sqrt{3}$ kV on the 32-kv side.

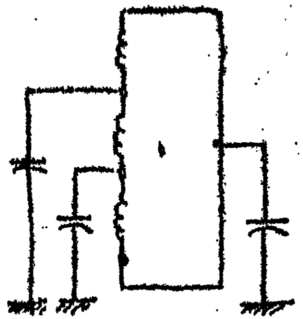
5. Floating delta connection

If transformer windings are connected in delta and nothing else, such as a line, is connected to it, then the delta is "floating." In a floating delta connection, the voltages to ground are not defined but only the voltages across the windings. This leads to a singular matrix with a respective error message termination. Therefore, either ground one terminal or add ground capacitances.





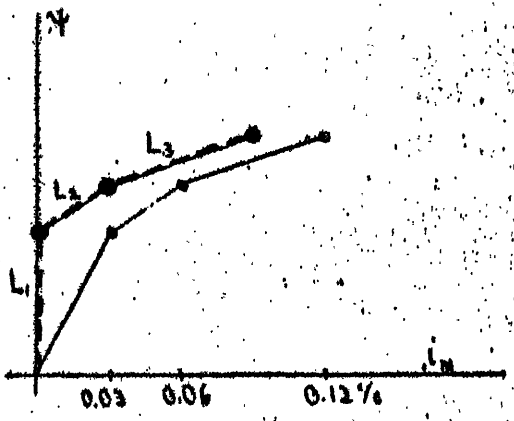
terminal C grounded



ground capacitances added

6. Saturation

The impedance matrix produced by the program does not include saturation effects. I think that saturation can be represented with sufficient accuracy by adding a nonlinear inductance (preferably as "switched inductance") across one winding only, say on the high side. This nonlinear inductance will be in parallel with the unsaturated value of the magnetizing inductance. Example: If the saturation curve is defined by 3 points at i_m = 0.03%, 0.06% and 0.12% and if 0.03% was used as magnetizing current for finding the impedance matrix, then the value of 0.03% must be subtracted in defining this nonlinear inductance (dashed line in Fig.). If the nonlinear inductance is modeled as "switched inductance" and if L_1 is ∞, simply use a very large number such as $L_1 = 10^{50}$.



7. User's instructions

See pages 94-96.

8. Test example

See pages 97 to 100.

7 AUXILIARY SUPPORTING ROUTINES

Several supporting computer routines are used in conjunction with the Transients Program proper, to generate or modify input data. Writeups for these routines are to be found on the following pages of this section. While originally used as separate programs, they have been pulled into the structure of the Transients Program for completeness.

To execute any one of these routines in place of any regular Transients Program data case (see Sect. 1. definition), one simply punches the correct key word in columns 1 onward of the first non-comment card. This is as per Section 1.0g , where the following 8 routines are available:

KEYWORD =

"XFORMER "	is a request for the transformer impedance-matrix routine of Section 7.1 ;
"SATURATION"	is a request for the magnetic-saturation routine of Section 7.2 ; it also provides access to the magnetic hysteresis-loop generating routine of Section 7.2a (for use with Type-96 element).
"WEIGHTING "	is a request for the weighting-function routine of Section 7.3 . This is preparation for the frequency-dependent representation of a mode of the continuously-transposed line of Section 1.27 .
"LINE CONSTANTS"	is a request for the overhead line constants calculation routine of Section 7.4 . Before 1976, this existed as a separate entity under the name of "BPA Line Constants Program".
"SEMLYEN SETUP"	is a request for the routine of Section 7.5 , which calculates transmission line (or cable) parameters which are needed for th EMTP modeling of the circuit using Semlyen recursive convolution. See "HAUER SETUP" .
"AMETANI SETUP"	is a request for the routine of Section 7.6 , which calculates transmission line (or cabl) parameters which are needed for the EMTP modeling of the circuit using Ametani piecewise-linear convolution.
"CABLE CONSTANTS"	is a request for the routine of Section 7.7 which calculates resistance, inductance, and capacitance matrices for cable systems.
"HAUER SETUP"	is a request for the very sophisticated r plac mer for "SEMLYEN SETUP" . See Section 7.8 for detail

Following this request card, data cards applicable to the appropriate routine (see following pages) are to be placed.

Note that if desir d, any or all of these supporting routines can be executed in the same computer run, sandwiched in any order among regular transients cases (if any).

7.1 "XFORMER" Routine

Supporting routine "XFORMER" is used to derive matrices [R] and [L] of Section 1.24, which can be used to provide a linear representation for a single-phase, two or 3-winding transformer. Punched card output of "XFORMER" are used as the branch cards of Section 1.24.

Section 1.25 describes the EMTP saturable "TRANSFORMER" component, which provides an EMTP representation for a transformer with an arbitrary number of windings. For most usage, the representation of Section 1.25 is prefered, and usage of the present section will not be required. But there are exceptions, so read on!

For 2-winding transformers, the saturable "TRANSFORMER" component of Section 1.25 is believed to be equivalent to or better (more general, and more convenient) than representation by means of matrices [R] and [L] (EMTP branches of type-code 51, 52, etc.). Hence it is not recommended that supporting routine "XFORMER" be used in the 2-winding case, except in very special cases.

But numerical instability has been observed in certain cases where 3-winding saturable "TRANSFORMER" components have been used. This is not in all cases, nor even in most cases. But in several cases between 1975 and 1977, trouble was encountered, as further discussed in Section 1.25. Hence supporting routine "XFORMER" continues to have production application, for 3-winding transformers.

Data-Deck Structure for 3-Winding Usage

Suppose that the user wants to generate Type 51-53 branch cards for the EMTP representation of one or more 3-winding single-phase transformers. His data deck then will have the following structure:

1. First comes a "BEGIN NEW DATA CASE" card (actually optional, as per Section 1.0a).
2. Next comes an "XFORMER" special-request card, which serves to transfer control to the overlay in question (UTPF overlay #41).
3. Next comes an optional "BRANCH" card (if any), which names the terminal nodes of the transformer windings for subsequent EMTP usage.
4. Next come four data cards which give electrical parameters of the transformer.
5. Repeat the data of Point 3 and Point 4 as many times as desired. Each such grouping is a separate data case within "XFORMER", corresponding to a different transformer. A blank card terminates these.
6. If the user wants to shut off the EMTP at this point (rather than execute a following EMTP data case), he should simply add a "BEGIN NEW DATA CASE" card at this point, followed by a blank card. This is as per Section 1.0b.

Format for Point 3 "XFORMER" Data ("BRANCH" card)

If the user wants punched-card output (variable "IPUNCH" of Point 4 "XFORMER" data), then terminal node names may be desired. Without such information, the Type 51-53 branch cards which will be punched will have fields "BUS1" and "BUS2" of columns 3-14 blank.

The user can supply branch names "BUS1" and "BUS2" for all transformer windings by means of the following card:

BRANCH	Type-51 (high)		Type-52 (medium)		Type-53 (low)	
	BUS1	BUS2	BUS1	BUS2	BUS1	BUS2
	A6	A6	A6	A6	A6	A6

Note that the key word "BRANCH" is punched in columns 1-6 . Then pairs of names are supplied for the three windings, with the high-voltage winding coming first (row 1 of the printed matrix; Type-51 branch card of the punched output); then comes the intermediate-voltage winding (row 2 of the printed matrix; Type-52 branch card of the punched output); finally there is the low-voltage winding (row 3 of the printed matrix; Type-53 branch card of the punched output).

Format for Point 4 "XFORMER" Data

For a 3-winding single-phase transformer, the Point 4 "XFORMER" data consists of four cards. The first of these has the following format:

NW	CMAGN	PBCUR		IPUNCH
I1	E9.0	E10.0		I8

NW ——— The number of transformer windings ("3" as used here).
(1)

CMAGN ——— The transformer magnetizing current in percent, consistent with the base power "PBCUR" .
(2-10)

PBCUR ——— Single-phase base power of the transformer in MVA., for use with the "CMAGN" specification.
(11-20)

IPUNCH ——— Flag which controls the possible punching of Type 51-53 branch cards as output:
(25-32)

- 0 ⟹ Yes, punch the cards;
- 1 ⟹ No punched card output.

Free-format separation and continuation characters "CSEPAR" and "CHCONT" will be used on all punched cards (see sample output to follow, and definition of Section 1.Og6). Of course the usage of such characters must be consistent, between the "XFORMER" run and the subsequent electric-network simulation which uses the punched cards.

The data is completed by three additional cards, each of which has four numbers punched on it. The following subscript meaning is assumed:

"1" ------ high voltage winding;

"2" ------ medium voltage winding;

"3" ------ low voltage winding.

Then the three data cards in question contain the following information:

$VOLT_1$	$PLOSS_{12}$	ZSC_{12}	PBZ_{12}
$VOLT_2$	$PLOSS_{13}$	ZSC_{13}	PBZ_{13}
$VOLT_3$	$PLOSS_{23}$	ZSC_{23}	PBZ_{23}
E10.0	E10.0	E10.0	E10.0

$VOLT_i$ ------ Voltage rating of winding number "i", in units of RMS kV.

$PLOSS_{ij}$ ------ Single-phase transformer load loss in kilowatts, when transmitting rated power between winding "i" and winding "j".

ZSC_{ij} ------ Short-circuit impedance of the transformer between winding "i" and winding "j", in units of per cent based on the power PBZ_{ij}.

PBZ_{ij} ------ Single-phase base power in MVA, upon which ZSC_{ij} is based.

<u>Sample "XFORMER" Data Case</u>

Consider 3-winding usage of "XFORMER" as per one of the data cases within UTPF Test Case #42. This has been set up as a separate EMTP data case, for purposes of illustration. A listing of this problem follows:

```
BEGIN NEW DATA CASE ~ Point 1 data
C     UTPF TEST CASE NO. 42 ------ INTERIOR SUBCASE TAKEN THEREFROM.
XFORMER ~ Point 2 data
BRANCH  NAME1  NAME2  NAME3  NAME4  NAME5  NAME6 ~ Point 3 data
3        0.3    83.3              0
       132.8    250.                      33.3 } Point 4 data
        66.4    56.8                [illegible]46 }
        13.2    56.8                [illegible]96 }
  Blank card ending "XFORMER" cases ~ Point 5 data
BEGIN NEW DATA CASE } ~ Point 6 data
  Blank card        }
```

EMTP line printer output of the solution then appears as shown below. Note that a listing of the punched cards is always obtained, to document the branch-card output (which will be used in subsequent EMTP electric-network simulations). The free-format usage of these cards should be evident. It is seen that a comma (",") is being used for the field-separation character "CSEPAR", and a dollar sign ("$") is being used for the continuation character "CHCONT". Since not redefined in the data case using the "FREE FORMAT" special request card of Section 1.0gf, this character choice was implicit to the EMTP being used (as defined within system-dependent module "SYSDEP" of UTPF overlay #1). Six data cards are used for the high-precision input of what would otherwise only require three cards, had the fixed-format specification of Section 1.24 been used.

```
ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP), CDC TRANSLATION PRODUCED AT THE BONNEVILLE POWER ADMINISTRATION, PORTLAND,
OREGON.  DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) =  [illegible]  [illegible]   ANY PLOTS BEAR THE SAME FIGURES.
IF IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE [illegible]-PAGE EMTP USER'S MANUAL DATED JANUARY, 1976.
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF  /LABEL/  EQUALS  [illegible]  INTEGER WORDS.
   10    10    10    5    10    5    15    10    5    5   35   50    1   20   50    4   2    5   1    1
--------------------------------------------------+--------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA | INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER B
                                                  0         1         2         3         4         5         6
                                                  0         0         0         0         0         0         0
--------------------------------------------------+--------------------------------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.              |BEGIN NEW DATA CASE
COMMENT CARD.                                     |C    UTPF TEST CASE NO. 42  ------   INTERIOR SUBCASE TAKEN THERE
REQUEST FOR TRANSFORMER IMPEDANCE-MATRIX ROUTINE. |XFORMER
NODE NAMES FOR PUNCHED BRANCH CARDS.              |BRANCH  NAME1 NAME2 NAME3 NAME4 NAME5 NAME6
NEW DEVICE.       3 .300000E+00 .633000E+02    -0 |3         0.3      63.3         0
WIND.   .132E+03  .256E+03   .678E+01   .833E+02  |1       132.8      256.        6.7      83.3
WIND.   .664E+02  .568E+02   .510E+01   .190E+02  |1        66.4      56.8        5.1      18.96
WIND.   .132E+02  .568E+02   .320E+01   .190E+02  |1        13.2      56.8        3.2      18.96

SINGLE-PHASE 3-WINDING TRANSFORMER.    'IMAGN' =   .30000 PER CENT BASED ON  63.300 MVA
VOLTAGE ACROSS WINDING                    LOSSES   IMPEDANCE BASED ON
      (KV)                                 (KW)    (PER CENT)  (MVA)
HIGH    132.80      HIGH   TO MEDIUM     256.30      6.7800    83.300
MEDIUM   66.40      HIGH   TO LOW         56.80      5.1000    18.960
LOW      13.20      MEDIUM TO LOW         56.80      3.2000    18.960

IMPEDANCE MATRIX AS REQUIRED FOR T.P. STUDIES (WITH 'X' IN OHMS AT THE POWER FREQUENCY)
                 R               X               R               X               R               X
HIGH       .4507137E+00    .7058197E+05
MEDIUM     .6653229E-01    .3526556E+05    .1126929E+00    .1764467E+05
LOW       -.5802603E-01    .7013580E+04   -.2901588E-01    .3537084E+04    .1153588E-01    .6973924E+03


80-COLUMN CARD-IMAGE LISTING OF PUNCHED-CARD OUTPUT FOLLOWS (TYPE-51-53 EMTP BRANCH CARDS).
-----------------------------------------------------------------------------------
         1         2         3         4         5         6         7         8
         0         0         0         0         0         0         0         0
-----------------------------------------------------------------------------------
51NAME1 NAME2                  .4507136759280E+00 ,     .7058196750567E+05 , ,,,,
52NAME3 NAME4                  .6653228709258E-01 ,     .3528359646672E+05 $
                               .1126928513759E+00 ,     .1764401526697E+05 , ,,,,
53NAME5 NAME6                 -.5802602976028E-01 ,     .7013580385482E+04 $
                              -.2901588397677E-01 ,     .3537083720582E+04 $
                               .1153587757842E-01 ,     .6973923570124E+03 , ,,,,
-----------------------------------------------------------------------------------


SHORT-CIRCUIT INPUT IMPEDANCES WHICH ARE OBTAINED FROM THE JUST-PRINTED IMPEDANCE MATRIX, BY REVERSE
COMPUTATION.   THIS IS SORT OF A CHECK ON THE COMPUTATION.
HIGH    TO MEDIUM         .63532         14.16964
HIGH    TO LOW           2.75456         47.34106
MEDIUM  TO LOW            .69676          7.40642
REPEAT OF PRECEDING CALCULATION, ONLY THIS TIME THE STARTING POINT WILL BE THE IMPEDANCE MATRIX WITH ALL
ELEMENTS ROUNDED TO FIVE DECIMAL DIGITS.
HIGH    TO MEDIUM         .63131         13.99977
HIGH    TO LOW        [illegible]        47.34462
MEDIUM  TO [illegible]  [illegible]       7.41954

BLANK CARD TERMINATING 'XFORMER' CASES.

ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP), CDC TRANSLATION PRODUCED AT THE BONNEVILLE POWER ADMINISTRATION, PORTLAND,
OREGON.  DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) =  [illegible]  13.04.03   ANY PLOTS BEAR THE SAME FIGURES.
IF IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE [illegible]-PAGE EMTP USER'S MANUAL DATED JANUARY, 1976.
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF  /LABEL/  EQUALS  [illegible]  INTEGER WORDS.
   10    10    10    5    10    5    15    10    5    5   30    1   20   55    4    2    5    1
--------------------------------------------------+--------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA | INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY
                                                  0         1         2         3         4         5         6
                                                  0         0         0         0         0         0         0
--------------------------------------------------+--------------------------------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.              |BEGIN NEW DATA CASE
BLANK TERMINATION-OF-RUN CARD.                    |
```

Interpretation of "XFORMER" Input Data Cards

There are only four distinct types of non-comment cards which might be read by "XFORMER". The first of these is the optional "BRANCH" card (Point 3 "XFORMER" data), which is interpreted as follows:

NODE NAMES FOR PUNCHED BRANCH CARDS.	1

The first of the cards which make up Point 4 "XFORMER" data is given the interpretation:

NEW DEVICE.	I6	E12.3	E12.3	I7	1
	NW	CMAGN	PBCUR	IPUNCH	

The remaining cards of Point 4 "XFORMER" data, one for each winding of the transformer, are interpreted as follows:

WIND.	E11.3	E11.3	E11.3	E11.3	1
	VOLT	PLOSS	ZSC	FBZ	

Finally, there is interpretation for the blank card which signals the end of data cases within "XFORMER" (Point 5 "XFORMER" data):

BLANK CARD TERMINATING "XFORMER" CASES.	1

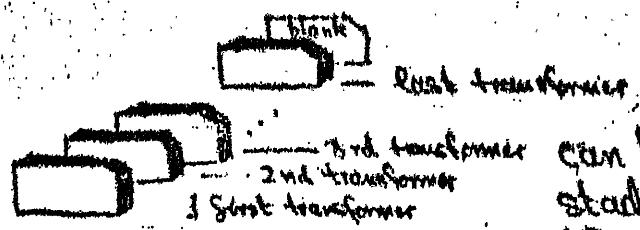
Possible problem with matrix singularity

If the user specifies too little magnetising current, then the admittance matrix becomes nearly singular, and it can not be inverted to give the desired matrices [R] and [L]. Floating-point miscellaneous data parameter "EPSILN" (see Section 1.0h) is used as a singularity tolerance (a default value is assigned in module "SYSDEP" of UTPF overlay #1). Should the user's data fail this check, the following message will be printed:

```
PROBLEM. ---- ADMITTANCE MATRIX FOR TRANSFORMER IS TOO CLOSE TO BEING SINGULAR TO BE INVERTIBLE.  HENCE
              THE INVERSION WILL BE SKIPPED.   PARAMETERS WHICH DOCUMENT THIS BREAKDOWN FOLLOW.
                             EPSILN                CII                   CA
```

USER'S INSTRUCTIONS
FOR PROGRAM
TO OBTAIN IMPEDANCE MATRIX OF TRANSFORMERS

INPUT: 2 cards for each 2-winding, single phase transformer,
4 cards for each 3-winding, single-phase transformer.



Any number of transformers can be studied with a single run by stacking as many sets of 2 cards (for 2-windg. transf.) or 4 cards (for 3-windg. transf.). Terminate stack with a blank card.

Two-winding, single-phase transformers

First card:

1	2 3 4 5 6 7 8 9 10	11 12 13 14 15 16 17 18 19 20
NO. OF WINDINGS	MAGNETIZING CURRENT in PER CENT based on power in columns 11-20	SINGLE-PHASE BASE POWER in MVA on which magn. current is based
2		
FORMAT	E9.0	E10.0

always punch [2] in column 1

It is accurate enough to use magn. current = exciting current.

Second card:

1 2 3 4 5 6 7 8 9 10	11 12 13 14 15 16 17 18 19 20	21 22 23 24 25 26 27 28 29 30	31 32 33 34 35 36 37 38 39 40	41 42 43 44 45 46 47 48 49 50
TAP SETTING in kV ACROSS WINDING		SINGLE-PHASE LOAD LOSSES in kW at rated power	SHORT-CIRCUIT INPUT IMPEDANCE in PER CENT based on power	SINGLE-PHASE POWER BASE in MVA on which impedance is based
HIGH SIDE	LOW SIDE			
Format E10.0	E10.0	E10.0	E10.0	E10.0

RMS-values. For wye-connections: $\frac{\text{phase-to-phase}}{\sqrt{3}}$;
for delta connections: phase-to-phase

is "average test impedance per cent Z," in BPA data book ("short-circuit input impedance" is correct name as defined in ANSI C57.12.90-1968 & IEEE Standard No. 262)

is "base kVA" in BPA data book (convert from kVA to MVA!)

Three-winding, single phase transformers

First card:

1	2–10	11–20
	MAGNETIZING CURRENT in PER CENT based on power in columns 11-20	SINGLE-PHASE BASE POWER in MVA on which magn. current is based
3		
	E9.0	E10.0

always punch 3 in column 1.

It is accurate enough to use magn. current = exciting current.

2nd to 4th card:

	1–10	11–20	21–30	31–40
	TAP SETTING in kV ACROSS WINDING	SINGLE-PHASE LOAD LOSSES in kW at rated power	SHORT-CIRCUIT INPUT IMPEDANCE in PER CENT based on power	SINGLE-PHASE POWER BASE in MVA on which impedance is based
	HIGH	HIGH-MEDIUM	HIGH-MEDIUM	HIGH-MEDIUM
	MEDIUM	HIGH-LOW	HIGH-LOW	HIGH-LOW
	LOW	MEDIUM-LOW	MEDIUM-LOW	MEDIUM-LOW
Format	E10.0	E10.0	E10.0	E10.0

Same comments as for 2-winding transformer (columns 1–10)

Same comments as for 2-winding transformer (columns 21–40)

OUTPUT:

Normal output on next page.

Error message if magnetizing current is too low to permit inversion of admittance matrix:

```
NGLE-PHASE 2-WINDING TRANSFORMER. IMAGN =-0.00000 PERCENT BASED ON  20.000 MV
LTAGE ACROSS WINDING                   LOSSES  IMPEDANCE BASED ON
   (KV)                                 (KW)    (PER CENT) (MVA)
H   110.00       HIGH    TO LOW        136.00   10.0000    20.000
H    30.00

MITTANCE MATRIX TOO CLOSE TO SINGULAR TO BE INVERTIBLE
```

96

Normal output

2-winding transformer

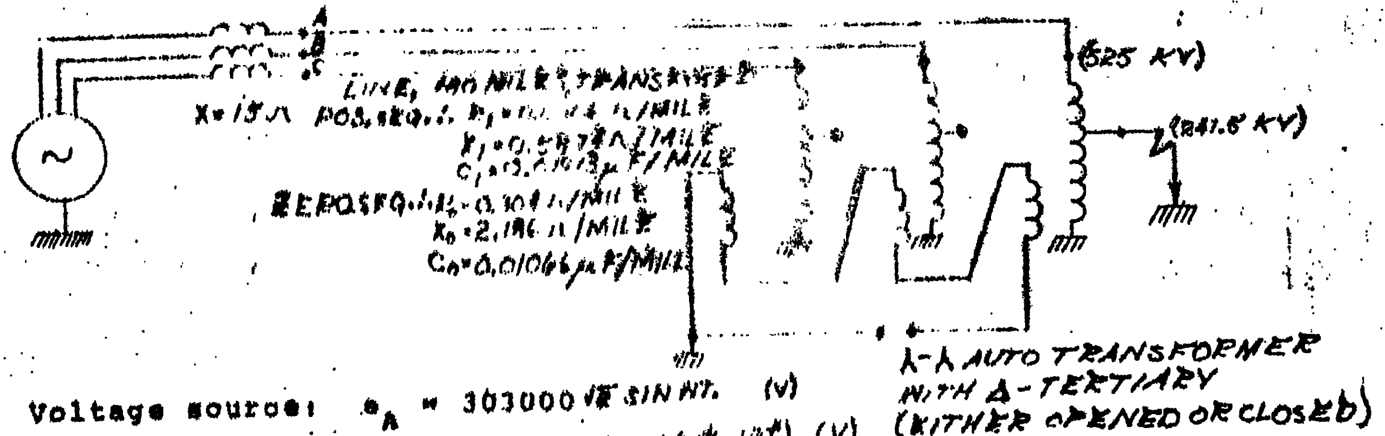
```
SINGLE-PHASE 2-WINDING TRANSFORMER. IMAGN = 2.00000 PERCENT BASED ON   6.667 MVA
VOLTAGE ACROSS WINDING                    LOSSES  IMPEDANCE BASED ON
     (KV)                                  (KW)   (PER CENT) (MVA)
HIGH    63.50       HIGH   TO LOW         45.37   10.0000     6.667
LOW     17.32

IMPEDANCE MATRIX AS REQUIRED FOR TRANSIENTS PROGRAM (X AT POWER FREQUENCY)
             R             X                R               X                P              X
HIGH     1.0270884E+00  3.0255441E+04
LOW     -2.8014443E-01  8.2441251E+03  7.6411648E-02  2.2508772E+03
WARNING.IF NOTHING CONNECTED TO WINDINGS IN DELTA, EITHER ADD CAPACITANCES OR GROUND ONE TERMINAL

SHORT-CIRCUIT INPUT IMPEDANCES OBTAINED FROM IMPEDANCE MATRIX        (TO AVOID UNDEFINED FLOATING)
HIGH   TO LOW              4.10426        60.28089
SAME, EXCEPT ELEMENTS IN IMPEDANCE MATRIX ROUNDED TO 5 DIGITS
HIGH   TO LOW              4.10419        60.32920
```

3-winding transformer

```
SINGLE-PHASE 3-WINDING TRANSFORMER. IMAGN =  .30619 PERCENT BASED ON 300.000 MVA
VOLTAGE ACROSS WINDING                    LOSSES  IMPEDANCE BASED ON
       (KV)                                (KW)   (PER CENT) (MVA)
HIGH   303.00       HIGH   TO MEDIUM       0.00     9.4600   300.000
MEDIUM 139.60       HIGH   TO LOW          0.00    42.3600   300.000
LOW     34.50       MEDIUM TO LOW          0.00    31.8420   300.000

IMPEDANCE MATRIX AS REQUIRED FOR TRANSIENTS PROGRAM (X AT POWER FREQUENCY)
             R              X               R                X                R                X
HIGH    -0.              9.9972154E+04
MEDIUM   0.              4.6050638E+04  0.                2.1218663E+04
LOW      0.              1.1376889E+04  0.                5.2421922E+03  0.                1.2963764E+03
WARNING.IF NOTHING CONNECTED TO WINDINGS IN DELTA, EITHER ADD CAPACITANCES OR GROUND ONE TERMINAL

SHORT-CIRCUIT INPUT IMPEDANCES OBTAINED FROM IMPEDANCE MATRIX      (TO AVOID UNDEFINED FLOATING)
HIGH   TO MEDIUM           0.00000        28.94763
HIGH   TO LOW              0.00000       129.54560
MEDIUM TO LOW              0.00000        20.66977
SAME, EXCEPT ELEMENTS IN IMPEDANCE MATRIX ROUNDED TO 5 DIGITS
HIGH   TO MEDIUM           0.00000        28.80753
HIGH   TO LOW              0.00000       129.25933
MEDIUM TO LOW              0.00000        21.32888
```

525

TEST CASE FOR 3-WINDING TRANSFORMER



Voltage source: e_A = 303000√2 SIN ωt (V)

e_B = 303000√2 SIN(ωt − 120°) (V)

e_C = 303000√2 SIN(ωt + 120°) (V)

Fault: System is energized at $t < 0$
single-line-to-ground fault on phase A of 241.5 kV
transformer terminal at $t=0$

Transformer data for each single phase unit (Covington bank):

$I_{magnetization}$ = 0.3 per cent based on 300 MVA (single-phase)

Short-circuit impedances (R ignored):

High to medium	9.46 per cent	based on 300 MVA (single-phase)
High to low	42.36 per cent	
Medium to low	31.84 per cent	

Tap settings: $\frac{525}{\sqrt{3}}$ kV / $\frac{241.5}{\sqrt{3}}$ kV / 34.5 kV

Results: On the next 2 pages, the voltages on the 525 kV-side and the currents on the 241.5 and 35 kV-side are shown,
(a) with the tertiary closed,
(b) with the tertiary open.

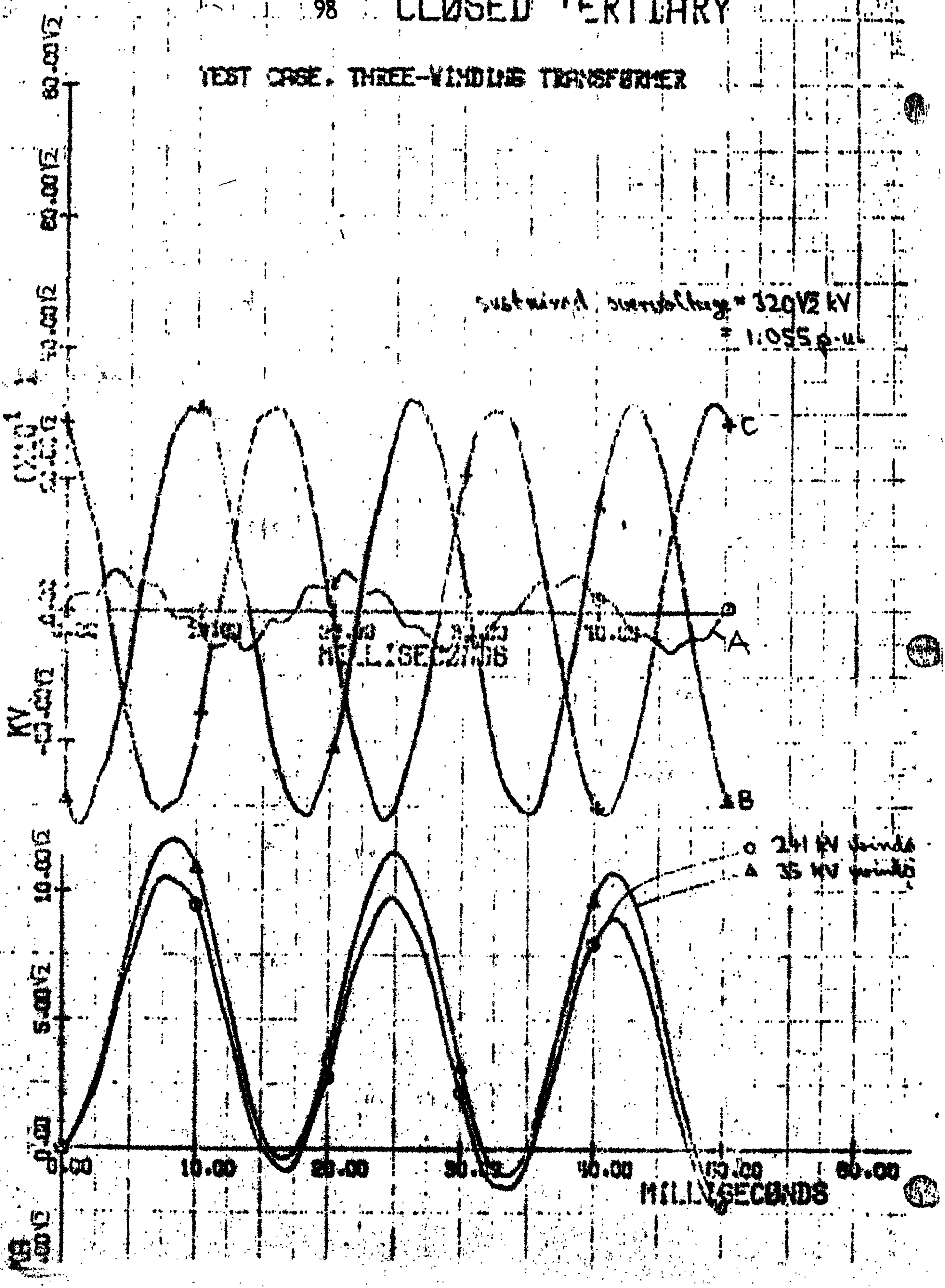
An open tertiary produces lower currents but higher overvoltages (1.42 p.u.).

The listing for the input data is attached as the last page.

98

CLOSED TERTIARY

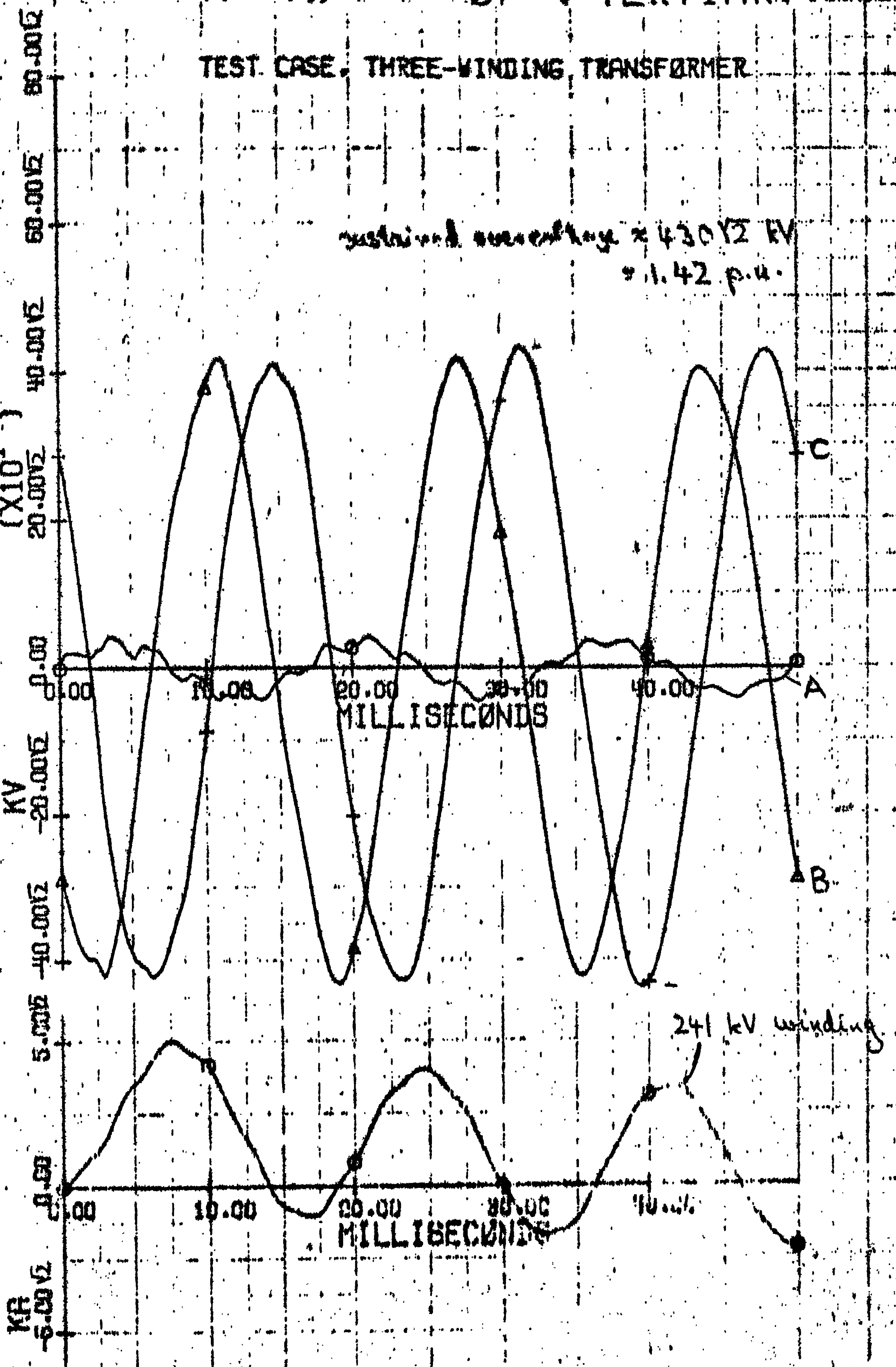
TEST CASE. THREE-WINDING TRANSFORMER



sustained overvoltage = 320√2 kV
= 1.055 p.u.

ØPEN TERTIARY

TEST CASE, THREE-WINDING TRANSFØRMER



CLOSED TERTIARY

```
TEST CASE, THREE-WINDING TRANSFORMER
RECORD OF INPUT - BRANCH DATA (R IN OHM, X IN OHM FOR    60.0 HZ, C IN MICROFARAD)
 0  SOURCA   S-A                 -0.          1.500E+01-0.
 0  SOURCB   S-B                 -0.          1.500E+01-0.
 0  SOURCC   S-C                 -0.          1.500E+01-0.
-1  S-A      R-A                  3.040E-01 2.186E+00 1.066E-02 1.800E+02 -E -0 ZSURGE=  737.53 TRAVE
-2  S-B      R-B                  3.080E-02 5.874E-01 1.915E-02 1.800E+02 -E -0 ZSURGE=  285.24 TRAVE
-3  S-C      R-C
 1  R-A                          -0.          9.9972E04-0.
 2  M-A                          -0.          4.6051E04-0.          -0.        2.1289E04-0.
 3  T-A      T-B                 -0.          1.1337E04-0.          -0.        5.2422E03-0.        -0.

 1  R-B               R-A                                                               1.2964E03-0.
 2  M-B
 3  T-B      T-C
 1  R-C               R-A
 2  M-C
 3           T-A
 0  M-A      SHORT               -0.          5.000E-03-0. } Small inductances were
 0  T-C                          -0.          5.000E-03-0. } inserted to measure the currents!           100
SWITCH          SHORT    0.        1.00000E+00 -0.          -0.

RECORD OF INPUT - SOURCE DATA                       DELTA-T=  1.000000E-04   T-MAX=  5.000000E-02
14     SOURCA  -0  3.030000E+02  6.000000E+01 -9.000000E+01 -0.              -0.             -1.000000E+00
14     SOURCB  -0  3.030000E+02  6.000000E+01 -2.100000E+02 -0.              -0.             -1.000000E+00
14     SOURCC  -0  3.030000E+02  6.000000E+01  3.000000E+01 -0.              -0.             -1.000000E+00
STEADY STATE OVERLAY ENTERED.
  STEADY STATE CALCULATIONS COMPLETE.

TRIANGULAR MATRIX WITHOUT SWITCH-NODES HAS   59 ELEMENTS

RESULTS SAVED ON FILE FOR PLOTTING. PLOTS WILL USE EVERY    1 CALCULATED POINTS ONLY

FIRST  3 RESULTS ARE NODE VOLTAGES
 NEXT  0 RESULTS ARE BRANCH VOLTAGES
FINAL  2 RESULTS ARE CURRENTS

STEP   TIME        R-A           R-B           R-C          M-A          T-C
                                                            SHORT
                                                                   SWITCH "SHORT " TO "
                                                                                   CLOSED AFTER 0. SEC.
   0 0.          -1.24292E+00 -2.86405E+02  2.87648E+02 -1.81899E-10 -1.76026E-07
 100 1.000E-02 -2.59486E+01  3.09287E+02 -1.56464E+02  9.45599E+00  1.09293E+01
 200 2.000E-02  4.25708E+01 -2.07887E+02 -2.84064E+01  2.80507E+00  3.64530E+00
 300 3.000E-02 -4.34182E+01  3.22811E+01  2.07642E+02  2.20759E+00  3.22378E+00
```

Section 7.1A

"TRELEG" ---- a supporting program designed
to generate Type 51,52,...
branch cards for 3-phase, 3-leg
core-type transformers.

Background

The 3-phase, 3-leg, core-type transformer has long been recognized as a problem for EMTP users. Some of the explanation is contained in the fourth and fifth pages of Section 1.25, and that material shall not be repeated here. If the user does not know what a 3-leg transformer is, refer to the sketches and discussion of Section 1.25 . Supporting program "TRELEG" (mnemonic derived from "three leg") accepts measurement and configuration data of the transformer as input, and punches EMTP branch cards (Type 51,52,...) for the transformer as output. Written as a separate program by Dr. Vladimir Brandwajn of Ontario Hydro, it was integrated into the EMTP by BPA during May of 1980.

For completeness and perspective, other references to the problem shall be mentioned. The first Newsletter (Ref. 32) mention is in issue No. 2, the article entitled "Model of Three-Leg Core Transformer" by Vladimir and Russ. Hermann had simultaneously and independently been working on the problem, ever since the 1978 Madison EMTP short course (see Ref. 8, Vol. VIII, 30 June 1978, page ADVA-16). Hermann's approach, which was based on the [A],[B] matrix formulation, is numerically advantageous in cases where magnetizing current is low, since he avoids the near singularity of the [R],[L] formulation. See his comments on page 15 of the just-cited Newsletter. But that intended reconciliation of the Vancouver and Toronto codes never took place. Because Vladimir had mailed us (at BPA) a punched card deck of his routine, and because he had written user instructions, it was this code which was frantically massaged and added to the EMTP early in May of 1980. Whether there will be later modifications remains to be seen.

As for Section 1.25 modeling, I would recommend avoiding the "TRANSFORMER THREE PHASE" option at this time. The big problem for all users has been determination of the zero-sequence reluctance R0 (there is no supporting program comparable to "TRELEG" for deriving this number). BPA never did use this modeling, largely because we can count the number of 3-phase transformers out here on the fingers of one hand (with several fingers to spare!), and because such transformers have not been the subject of recent study interest. Also, the EMTP Newsletter article by Vladimir and Russ cast doubt on the validity of such ("old") representation, though I remain skeptical of the results (there are many ways to get wrong answers out of the EMTP, and not all of them can be blamed on defective modeling!). So, if the user has a 3-leg unit, use "TRELEG" , and complain to Toronto (not Portland) if results are less than pleasing!

So, on to the user instructions. The material immediately below was written by Vladimir; it was extracted from the first five pages of USER'S INSTRUCTIONS dated July 24, 1979. The final two pages of that memo constituted an example which is no longer applicable due to input/output format changes. Instead, I have appended a current ("M27." ; May, 1980) solution of one of Vladimir's numerous test cases at the end.

1006

USER'S INSTRUCTIONS July 24 1979

For the program to calculate impedance matrix of a three-legged core transformer

1.0 General Remarks

The effects of a three-legged core in a transformer are apparent in the different values determined for short-circuit impedances in positive and zero sequence. These values are used by the program to calculate a (N×3) × (N×3) impedance matrix model (N = number of windings on any leg, presently N ≤ 5). It is also possible to use this program to calculate an N XN matrix to represent a single-legged core, a shell type, or a 5 leg core transformer. In the latter cases, the values of the impedances (short-circuit and magnetizing) will be equal in both sequences.

The program accepts data for short-circuit tests performed with up to two of the windings connected in delta. This is the standard form in which a manufacturer will provide test data.

The data must be input so that delta connected windings appear last. A further, and occasionally conflicting program assumption is that the windings are concentrically located on the core, and input in the order from outer to inner winding. When windings are not concentric, or when the delta connected windings are not innermost on the core, the program provides for the user to retain delta connected windings as the last windings, and to provide the magnetizing impedance of each winding. In the absence of any test data, the positive sequence magnetizing impedance of windings in per unit can be assumed to increase with increasing diameter, while the zero sequence magnetizing impedance decreases. The variation from one winding to another will be approximately equal to the positive sequence short-circuit reactance between them. It is not believed that this approximation of magnetizing impedances has any significant effect on the resulting model.

2.0 Form of DATA Input

Class I

Card #1

N, NDELTA, f, SBVA
FORMAT (1x, 2I2, 2E12.0)
N = # of windings
NDELTA = # of delta winding (≤ 2)
f = frequency in Hz (60 in North America)
SBVA = base MVA (3-phase rating)

Class II (present only if NDELTA = 2)

Card #2 Through 4 (exactly 3 cards)

TPKMR, TPKMX
FORMAT (1X, 2E12.0)
TPKMR, TPKMX are real and imaginary parts of the positive sequence test between two delta windings.

Card #3

IDT
FORMAT (1X,I2)
IDT - # of wye winding for which zero sequence test with two delta windings closed is performed.

Card #4

TZKMR, TZKMX
FORMAT(1X, 2E12.0)
TZKMR, TZKMX are real and imaginary parts of the zero sequence test between wye and two delta windings.

Class III

Card #5 through $5+\frac{(N-1)(N-2)}{2}+1$ (for the case with NDELTA = 2)

If NDELTA < 2 cards #5 and up become card #2 through card # $2+\frac{(N-1)N}{2}+1$

Input: I, J, TPR, TPX, TZR, TZX
FORMAT (1X, 2I2, 4E12.0)

I&J - numbers of windings between which the test has been conducted TPR, TPX - real and imaginary parts of the positive sequence test in p.u.
TZR, TZX - real and imaginary parts of the zero sequence test in p.u.

Class III data has to be terminated with a blank card.

Class IV

One card specifying the key (KZOUT) to determine whether the output impedance matrix is to be in p.u. or in ohms.
KZOUT
FORMAT (1X, I2)
If KZOUT is zero - output in p.u., otherwise impedance matrix is in ohms.

Class V

Exactly N+1 cards containing winding number, rated voltage of the winding, indicator of delta windings and the node names to be used by the program in punching the branch impedance cards.

J, INDD, VR(J), R(J), NA(I), NB(I), NA(I1), NB(I1), NA(I2), NB(I2)
FORMAT (1X, I2, 1X, I1, 1X, 2E12.0, 6A6)
J = winding number (delta windings should always have the highest numbers!)

INDD = 0 - for Y windings
1 - for Delta windings
VR(J) = rated voltage of winding J, rms
R(J) = dc resistance of winding J
NA(I), NB(I),... - node names for phases A,B&C of winding J,
Class V data has to be terminated with a blank card.

Card VI

NT - key for either reading the magnetizing impedances (XPOZ, XZERO) of the windings or for using an approximation to calculate them.

FORMAT (1X, I2)
NT = 1 in the case when magnetizing impedances are known for each winding, otherwise it is assumed that XPOZ and XZERO is known only for the first winding.

Class VII

One or N cards containing values for magnetizing impedances in positive and zero sequence for the first (when NT=1) or all the windings.
XPOZ , XZERO
FORMAT (1X, 2E12.6)

Note that when XPOZ and XZERO are known for each winding they should be entered in order corresponding to the assigned number starting from the lowest number (see Class V data cards).
Class VII data has to be terminated with a blank card in this case.

3.0 Interpretation of Program's Output

The impedance matrix produced by the program is symmetrical and is represented by its lower triangular part only. This portion of the matrix is stored in one-dimensional array by using index transformation:
K = J+I+(I-1)/2, where I&J are indexes for row and column number of the matrix element and K - corresponding index for the same element of the matrix in the vector form. In general the transformer matrix is in the following form:

$$
\begin{array}{ll}
\text{winding } \#1_a & S_{11} \\
\text{winding } \#2_a & S_{12} \quad S_{22} \\
\cdots\cdots\cdots\cdots & \cdots\cdots \\
\text{winding } \#N_a & S_{1N} \cdots\cdots S_{NN} \\
\text{winding } \#1_b & M_{11} \cdots\cdots M_{1N} \quad S_{11} \\
\text{winding } \#2_b & M_{12} \cdots\cdots M_{2N} \quad S_{12} \quad S_{22} \\
\cdots\cdots\cdots\cdots & \cdots\cdots\cdots\cdots \\
\text{winding } \#N_b & M_{1N} \cdots\cdots M_{NN} \quad S_{1N} \cdots\cdots S_{NN} \\
\text{winding } \#1_c & M_{11} \cdots\cdots M_{1N} \quad M_{11} \cdots\cdots M_{1N} S_{11} \\
\text{winding } \#2_c & M_{12} \cdots\cdots M_{2N} \quad M_{12} \cdots\cdots M_{2N} S_{12} S_{22} \\
\cdots\cdots\cdots\cdots & \cdots\cdots\cdots\cdots\cdots\cdots \\
\text{winding } \#N_c & M_{1N} \cdots\cdots M_{NN} M_{1N} \cdots\cdots M_{NN} S_{1N} \cdots\cdots S_{NN}
\end{array}
$$

Sij denotes coupling between windings I and J on one leg of the transformer and Mij - between winding I on one leg and winding J on another leg.

In addition to providing a set of printed answers, the program produces a set of cards to be used in the EMTP. The data are punched in a free format as explained in the EMTP User's Manual.

Illustrative usage of "TRELEG" to generate Type 51-59 branch cards.

Consider first the line printer output corresponding to a 3-phase, 3-leg, core-type transformer:

```
ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP), DIGITAL (DEC) VAX-11/780 TRANSLATION AS USED BY BPA IN PORTLAND, OREGON  97208
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) = 05/21/80  11.51.41  [illegible]                                   VERSION M32.
IF IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE REFERENCE EMTP USER'S MANUAL DATED NOVEMBER, 1977.
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF   /LABEL/  EQUALS 200314  INTEGER WORDS.       303  1050  2500   30  9500
  125  4100  3000   50   100   190   150    3  1000   400    3    4   10  4500   500   12   200  1000    3  3700
-----------------------------------------------------------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA | INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARAC
                                                  |         1         2         3         4         5         6         7
                                                  |         0         0         0         0         0         0         0
-----------------------------------------------------------------------------------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.              |BEGIN NEW DATA CASE
REQUEST FOR TRANSFORMER IMPEDANCE-MATRIX ROUTINE. |XFORMER                                  33.
TRELEG,    3    1    0.60000E+02    0.75000E+03   | 3 1    60.          750.0
TEST.      2    1    0.17000E-01    0.11000E+00   | 2 1  .0017          .11         .0051        .115
TEST.      3    1    0.41000E-02    0.16000E+00   | 3 1  .0041          .16         .0096        .284
TEST.      3    2    0.44000E-02    0.20000E+00   | 3 2  .0044          .2          .0143        .136
BLANK CARD ENDING TESTS.                          |BLANK CARD ENDING MEASUREMENTS.
RZOUT =    1                                      | 1
WINDING.   1    0    0.24497E+03    0.47100E+00   | 1 0  244.9731740 .471     HIGHA      HIGHB      HIGHC
WINDING.   2    0    0.13886E+03    0.79980E-01   | 2 0  138.8640646 .079976  LOWA       LOWB       LOWC
WINDING.   3    1    0.28000E+02    0.11200E-01   | 3 1  28.         .01120   TERTA TERTIATERTIB TERTIBTERTICTERTA
BLANK CARD ENDING WINDINGS.                       |BLANK CARD ENDING WINDINGS.
KEY  "K0"    1                                    | 1
XPOZ, XZERO =    0.10000E+03    0.10000E+01       | 100.0     1.
XPOZ, XZERO =    0.99970E+02    0.11100E+01       | 99.97     1.11
XPOZ, XZERO =    0.99670E+02    0.11100E+01       | 99.67     1.11
BLANK BOUNDING RECORD.                            |BLANK CARD END MAGNETIZING IMPEDANCES.


**********   80-COLUMN CARD-IMAGE LISTING OF UNIT-7 PUNCHED CARDS.   *******
-------------------------------------------------------------------------------
        1         2         3         4         5         6         7         8
        0         0         0         0         0         0         0         0
-------------------------------------------------------------------------------
51,HIGHA ,      ,,,               0.471000000000E+00,  0.221333333341E+05 ,,,,,
52,LOWA  ,      ,,,              -0.644793103119E-01,  0.107059927425E+05 ,
                                  0.394790000000E-01,  0.514221199959E+04 ,,,,,
53,TERTA ,TERTIA,                -0.362559494697E-01,  0.215874652794E+04 ,
                                 -0.357194214476E-01,  0.103714560936E+04 ,
                                  0.112800000000E-01,  0.209767040000E+03 ,,,,,
54,HIGHB ,      ,,,               0.000000000000E+00, -0.110000000000E+05 ,
```

⁝ Etc. ⁝

```
59,TERTIC,TERTA ,,,              -0.494350580079E-01, -0.105342221589E+04 ,
                                 -0.322054558972E-01, -0.509850507464E+03 ,
                                  0.000000000000E+00, -0.102796000000E+03 ,,,,,
                                 -0.494356580079E-01, -0.106342221589E+04 ,
                                 -0.322054558972E-01, -0.509850507464E+03 ,
                                  0.000000000000E+00, -0.102796000000E+03 ,,,,,
                                 -0.362559494397E-01,  0.215874652794E+04 ,
                                 -0.357194214476E-01,  0.103714560936E+04 ,
                                  0.112800000000E-01,  0.209767040000E+03 ,,,,,
-- --- - ----------------------------------------------------------------------


BLANK CARD ENDING "TRELEG" CASES.                 |BLANK CARD ENDING "TRELEG" DATA CASES.

CORE STORAGE FIGURES FOR PRECEDING DATA CASE NOW COMPLETED.  --------------------------------------  PRESENT   PROGRAM
A VALUE OF  -9999 INDICATES DEFAULT, WITH NO FIGURE AVAILABLE.                                        FIGURE     LIMIT (NAME
    SIZE LIST 1.   NUMBER OF NETWORK NODES.                                                            -9999       303 (LBUS
```

Here the printed listing of the unit-7 output was abridged because a separate listing of these card images is to be provided:

```
51,HIGHA ,      ,,,          0.471000000000E+00,  0.221333333341E+05 ,,,,,
52,LOWA  ,      ,,,         -0.644793103119E-01,  0.107059927425E+05 ,
                             0.394790000000E-01,  0.514221199959E+04 ,,,,,
53,TERTA ,TERTIA,,,         -0.362559494697E-01,  0.215874652794E+04 ,
                            -0.357194214476E-01,  0.103714560936E+04 ,
                             0.112800000000E-01,  0.209767040000E+03 ,,,,,
54,HIGHB ,      ,,,          0.000000000000E+00, -0.110000000000E+05 ,
                            -0.733191019974E-01, -0.527370725120E+04 ,
                            -0.494356580079E-01, -0.106342221589E+04 ,,,,,
                             0.471000000000E+00,  0.221333333341E+05 ,,,,,
```

TOOF

```
55,LOWB  ,      ,$$     * -0.733191039974E-01, -0.527320725720E+04 $
                           0.000000000000E+00, -0.252774399980E+04 $
                          -0.325054568924E-01, -0.509650587464E+03 ,,,,,
                          -0.546793103319E-01,  0.107059927425E+05 $
                           0.299750000000E-01,  0.514227199959E+04 ,,,,,
56,TERTB ,TERTIB,,$       -0.494335690078E-01, -0.106342221589E+04 $
                          -0.325054568924E-01, -0.509650587464E+03 $
                           0.500000000000E+00, -0.102798080000E+03 ,,,,,
                          -0.362558943697E-01,  0.215874652794E+04 $
                          -0.357184214476E-01,  0.103714560936E+04 $
                           0.112800000000E-01,  0.209767040000E+03 ,,,,,
57,HIGHC ,      ,$$        0.050000000000E+00, -0.110000000004E+05 $
                          -0.733191039974E-01, -0.527320725720E+04 $
                          -0.494335690078E-01, -0.106342221589E+04 ,,,,,
                           0.050000000000E+00, -0.110000000004E+05 $
                          -0.733191039974E-01, -0.527320725720E+04 $
                          -0.494335690078E-01, -0.106342221589E+04 ,,,,,
                           0.811000000000E+05,  0.233333333341E+08 ,,,,,
58,LOWC  ,      ,$$       -0.733191039974E-01, -0.527320725720E+04 $
                           0.000000000000E+00, -0.252774399980E+04 $
                          -0.325054568924E-01, -0.509650587464E+03 ,,,,,
                          -0.733191039974E-01, -0.527320725720E+04 $
                           0.000000000000E+00, -0.252774399980E+04 $
                          -0.325054568924E-01, -0.509650587464E+03 ,,,,,
                          -0.546793103319E-01,  0.107059927425E+05 $
                           0.299750000000E-01,  0.514227199959E+04 ,,,,,
59,TERTIC,TERTA ,$$       -0.494335690078E-01, -0.106342221589E+04 $
                          -0.325054568924E-01, -0.509650587464E+03 $
                           0.000000000000E+00, -0.102798080000E+03 ,,,,,
                          -0.494335690078E-01, -0.106342221589E+04 $
                          -0.325054568924E-01, -0.509650587464E+03 $
                           0.000000000000E+00, -0.102798080000E+03 ,,,,,
                          -0.362558943697E-01,  0.215874652794E+04 $
                          -0.357184214476E-01,  0.103714560936E+04 $
                           0.112800000000E-01,  0.209767040000E+03 ,,,,,
```

Closer look at input data:

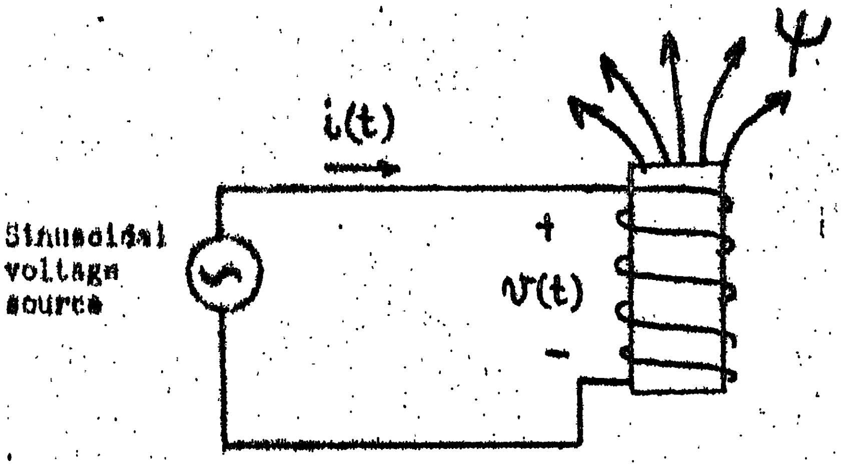
```
BEGIN NEW DATA CASE
XFORMER                                  33.
   3 1     60.          750.0
   1 2   .0017          .13         .0057        .115
   1 3   .0042          .35         .0096        .268
   2 3   .0044          .2          .0143        .136
BLANK CARD ENDING MEASUREMENTS.
   1
   1 0   288.6751346  .473       HIGHA      HIGHB      HIGHC
   2 0   138.5640646  .029875    LOWA       LOWB       LOWC
   3 1    28.         .01128     TERTA TERTIATERTB TERTIBTERTICTERTA
BLANK CARD ENDING WINDINGS.
   1
   100.0        1.
    99.87       1.13
    99.67       1.33
BLANK CARD END MAGNETIZING IMPEDANCES.
BLANK CARD ENDING "TRELEG" DATA CASES.
BEGIN NEW DATA CASE
```

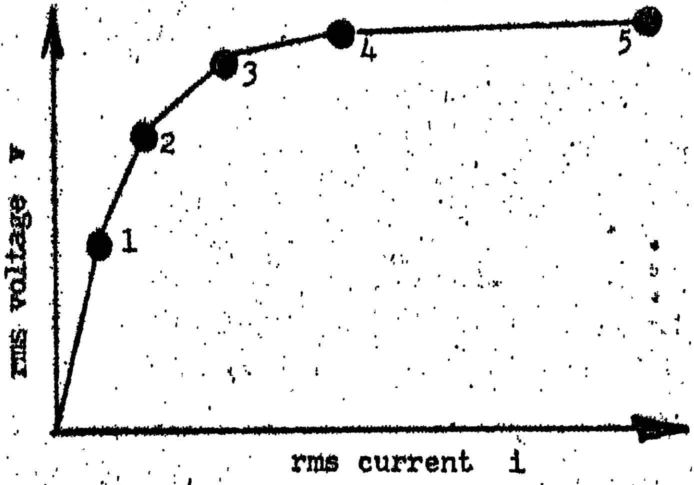
request for "TRELEG" by using "33." punched in cols. 38-40 of "XFORMER" card

CONVERT ---- A supporting program designed to convert rms v-i saturation curves into peak ψ-i curves

PURPOSE

Specification for nonlinear inductors requires a flux-current (ψ - i) saturation curve as per Section 1.33 of the User's Manual for the Transients Program. Yet typical test data consists of rms voltage and current readings corresponding to the configuration shown. With impressed sinusoidal voltage, an rms reading of the non-sinusoidal current into the winding is obtained. Program CONVERT is designed to convert from the user's rms v-i curve to the ψ-i curve needed by the Transients Program.





ASSUMPTIONS

The user inputs his v-i curve as a sequence of points, with linear interpolation between these values assumed. The output ψ-i curve is likewise piecewise-linear with the same number of points; it is exact, except for approximations:

1. The use of linear interpolation between points.
2. The use of finite-difference approximation to sinusoidal excitation. One-degree step-size is used, along with trapezoidal-rule integration where needed.
3. Hysteresis is ignored.

INPUT DATA FORMAT

Each case to be run consists of a miscellaneous-data card, followed by cards which supply the (I_{rms}, V_{rms}) break-points, followed by a 9999- card. A blank card should be placed after the last such data case, to end execution of program CONVERT .

FREQ	VBASE	PBASE	IPUNCH	KTHIRD
E8.0	E8.0	E8.0	I8	I8

FREQ —— Frequency of the sinusoidal excitation, in Hz.

VBASE —— Base voltage in kV , on which the input points are based.

PBASE —— Base power in MVA , on which the input points are based.

IPUNCH —— Parameter controlling the punched-card output of the derived flux-current curve:

$$\begin{cases} 0 \Rightarrow \text{Yes, the curve will be punched.} \\ 1 \Rightarrow \text{No punched output.} \end{cases}$$

The cards are punched one point per card, using a 2E16.8 format.

KTHIRD —— Zero or blank field will produce only first-quadrant output; unity will produce both the third and first quadrant points (the full curve).

The (I_{rms}, V_{rms}) points are next —— one per card as per the format below, starting with the point closest to the origin and then moving continuously away. The curve must be single valued, with not over 100 points. No point (0, 0) for the origin should be inputted. Values are in per unit on the previously-specified base, where

$$I_{base} = P_{base} / V_{base} \qquad I_{rms}\,[\text{p.u.}] = I_{rms}\,[\text{amps}] / I_{base}\,[\text{amps}]$$

$$V_{rms}\,[\text{p.u.}] = V_{rms}\,[\text{kV}] / V_{base}\,[\text{kV}]$$

Terminate with a 9999-card.

I_{rms} [p.u.]	V_{rms} [p.u.]
E16.0	E16.0

1–16
9999

Alternate Input of Incremental Inductance vs. Current Characteristic

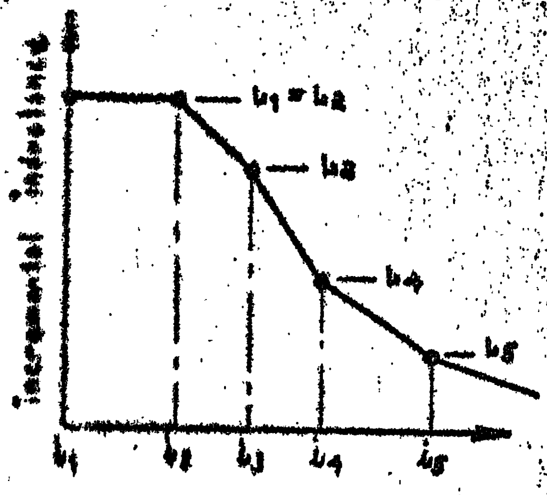
Instead of an rms I-V characteristic, the user has the option of inputing a current vs. incremental inductance characteristic. Trapezoidal rule of integration is then used in this case, to convert the inductance curve into the desired output curve of flux vs. current:

$$\psi(i) = \int_0^{i} L(\eta)\,d\eta \qquad \psi_1 = 0$$

$$\psi_k = \psi_{k-1} + \left\{ \frac{L_k + L_{k-1}}{2} \right\} (i_k - i_{k-1}) \qquad k = 2, 3, \ldots$$

537

In order to use this special inductance-input option, the following modification of preceding rules must be observed:



1. Punch the field "FREQ" of columns 1-8 equal to -1.0 . This is the special request flag for inductance-input.

2. Leave fields "VBASE" (cols. 9-16) and "PBASE" (columns 17-24) blank or punched with zero if the supplied characteristic will be in units of amps and henries . Nonzero values are taken to be scaling factors by which the user's breakpoint values are to be multiplied in order to produce amps and henries :

   VBASE = multiplying factor for input current coordinates;

   PBASE = multiplying factor for input inductance coordinates.

3. The current vs. incremental inductance characteristic is to be punched in columns 1-32 as per the following format, terminated by a 9999-card:

i_k	L_k
E16.0	E16.0

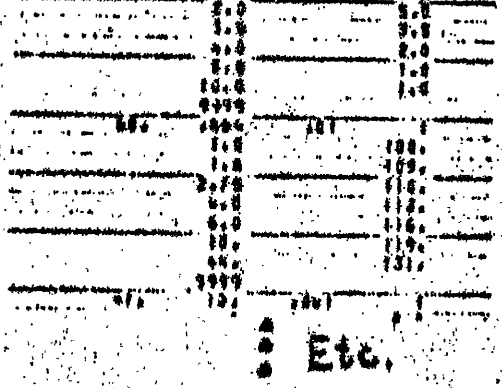
9999

4. The current breakpoints i_k must be monotone increasing, starting with value zero. Incremental inductance values $L_k = d\Psi/di$ at current value $i = i_k$ must all be positive. There also must be two or more points defining the characteristic.

5. Variable "IPUNCH" controls punched-card output. It might be mentioned that the (0.0, 0.0) point of the derived $i-\Psi$ curve is printed, but is not punched. This is because usage with type-98 pseudo-nonlinear reactors (Section 1.29) and saturable transformers (Section 1.25) requires that the origin-point be omitted.

SAMPLE PROBLEM

The data listing at the right shows card images associated with the first two of several conversion cases which were run at the same time using Program CONVERT. Resulting EMTP line-printer output is displayed on the following page.


SATURATION

9999

9999

Etc.

```
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) = 12/05/75  11.07.47  ANY PLOTS BEAR SAME FIGURES.
ELECTROMAGNETIC TRANSIENTS PROGRAM OF THE BONNEVILLE POWER ADMINISTRATION, PORTLAND, OREGON.
IF IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE 156-PAGE USER'S MANUAL.
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF   /LABEL/   EQUALS   [illegible]  INTEGER WORDS.
  250   300   500   100  1500    40   500  [illegible]    75    55    51    53    5   [illegible]   52    1    2    5
--------------------------------------------------------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA : INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER.
                                                  0         1         2         3         4         5         6         7         8
                                                  0         0         0         0         0         0         0         0         0
--------------------------------------------------------------------------------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.             |BEGIN NEW DATA CASE
COMMENT CARD.                                    |C     OTHER FLT CASE NO. 42
COMMENT CARD.                                    |C     TEST OF MAGNETIC-SATURATION ROUTINE. THE SUPPORTING PROGRAM WHICH
COMMENT CARD.                                    |C     CONVERTS AN RMS SATURATION CURVE OF V VS. I TO FLUX VS. CURRENT.
REQUEST FOR MAGNETIC-SATURATION ROUTINE.         |SATURATION
MISC. CONST.   -.100E+01  .130E+02  .100E-02  1 |    -1.       10.    .224   .
(I, L) POINT.      .0          .500000E+01      |               0.0           5.0
(I, L) POINT.      .200000E+01  .500000E+01     |               2.0           5.0
(I, L) POINT.      .389400E+01  .350000E+01     |               3.8           3.5
(I, L) POINT.      .400000E+01  .230000E+01     |               4.0           2.3
(I, L) POINT.      .500000E+01  .100000E+01     |               5.0           1.0
(I, L) POINT.      .130000E+02  .100000E+01     |              13.0           1.0
SPECIAL TERMINATION-OF-POINTS CARD.              |              9999

DERIVED SATURATION CURVE GIVING PEAK CURRENT VS. FLUX
      ROW                 CURRENT (AMP)                   FLUX (VOLT-SEC)
           ----------------------------------------------------------------------------------------
           REMEMBER.   THE JUST-COMPLETED CONVERSION BEGAN WITH CURRENT VS. INCREMENTAL INDUCTANCE
           CHARACTERISTICS, DUE TO MISCELLANEOUS DATA PARAMETER [illegible] OF COLUMNS [illegible]
            -1.0  .   TRAPEZOIDAL RULE INTEGRATION OF THE [illegible] CURVE WAS USED TO [illegible] FLUX.
           ----------------------------------------------------------------------------------------
        1                  .000000.000                    .000-0.0000
        2                26.0000000000                    .[illegible]
        3                33.0000000000                    .[illegible]
        4                43.[illegible]                   .[illegible]
        5                58.[illegible]                   .[illegible]
        6               133.[illegible]                   .[illegible]
MISC. CONST.    .[illegible]E+02  .50[illegible]E+30  .1[illegible]E-01   1 |     82.     .[illegible]    .01     1
(I, V) POINT.      .[illegible]E+01   .[illegible]E+03  |               [illegible]            102.
(I, V) POINT.      .[illegible]E+01   .105[illegible]E+03  |             4.6            105.
(I, V) POINT.      .275[illegible]E+01   .[illegible]E+03  |              2.75           [illegible]
(I, V) POINT.      .[illegible]E+01   .[illegible]E+03  |               [illegible]            [illegible]
(I, V) POINT.      .[illegible]E+01   .115[illegible]E+03  |               [illegible]            [illegible]
(I, V) POINT.      .[illegible]E+02   .119[illegible]E+03  |               [illegible]            119.
(I, V) POINT.      .[illegible]E+02   .131[illegible]E+03  |               [illegible]            131.
SPECIAL TERMINATION-OF-POINTS CARD.              |              9999

DERIVED SATURATION CURVE GIVING PEAK CURRENT VS. FLUX
      ROW                 CURRENT (AMP)                   FLUX (VOLT-SEC)
        1                  .5[illegible]                  .[illegible]
        2                21.2533978237                 249.[illegible]
        3                57.2429412031                 261.5[illegible]
        4                99.4053477329                 273.996.[illegible]
        5               154.6164576772                 281.[illegible]
        6               236.1828264049                 295.[illegible]
        7               [illegible]21.7672713236       296.[illegible]
        8              1031.6452379497                 325.38[illegible]

CHECK OF DERIVED CURVE BY INDEPENDENT REVERSE COMPUTATION.  ASSUMING SINUSOIDAL VOLTAGE (FLUX) AT LEVEL OF EACH POINT,
RMS CURRENT IS FOUND NUMERICALLY.  THIS CURVE SHOULD BE EQUAL TO THE ORIGINAL I-V POINTS INPUTTED.
 ROW      CURRENT IN P.U.     VOLTAGE IN P.U.
   2        1.33000603         109.00000300
   3        1.63000006         105.00000003
   4        2.75000000         113.00000000
   5        4.[illegible]      113.[illegible]
            6.00000000         116.00000000
   7       16.[illegible]      119.00000000
   8       [illegible]         131.00000000
MISC. CONST.   -.100E+01  .100E+02  .100E-02   1 1     -1.      10.     .001        1
(I, L) POINT.      .200000E+01   .500000E+01    |                                    2.0
```

Case 1

U vs. i

input

Case 2

V vs. I

input

Section 7.2A

HYSDAT -- A supporting routine designed to provide the hysteresis loop required by a type-96 element given the type of core material and the saturation values of flux and current.

Purpose

Required input data for a type-96 hysteretic inductor includes the major loop characteristic specified in terms of flux and current (ψ-i). (See Section 1.30a). However it is anticipated that such transformer data, often times, will not be available, therefore an attempt will be made here to catalogue the hysteresis charasoteristics for several common core materials.

Input Data Format

This support routine is requested as follows: on the first card the keyword "SATURATION" is punched beginning in column one; the next card has the value 88. in the FREQ field. The next two cards then specify the necessary input data.

KEYWORD
SATURATION

FREQ
E8.0

ITYPE	LEVEL	IPUNCH
I8	I8	I8

CURSAT	FLXSAT
E8.0	E8.0

ITYPE -- This is used to specify the type of material as follows:

ITYPE = 1 is Armco M4 oriented silicon steel

LEVEL -- Level of accuracy desired (1, 2, 3, or 4).

The level of accuracy is specified by the number of points used to define the loop. The specific number of points in each level may vary from material to material but the following values are given as a rough idea:

LEVEL	# of points
1	4-5
2	10
3	15
4	20-25

Unless space or time constraints should prove to be important, level 3 or 4 is suggested.

IPUNCH -- Parameter controlling the punched-card output of the derived flux-current loop;

0 Yes, the curve will be punched

1 No punched output

The cards are punched one point per card, using a 2E16.7 format.

CURSAT -- The current coordinate of the positive saturation point for the actual reactor being specified, (i.e. the point in the 1st quadrant of the flux-current plane where the hysteresis loop changes from being multivalued to singlevalued).

FLXSAT -- The flux coordinate of the positive saturation point

Recall that the shape of the hysteresis loop for an inductor depends primarily on the material of the core, while the scaling of the hysteresis loop depends on geometry, the number of turns, and other factors of the actual construction. What is stored in this routine is essentially the shape of the loop for the material specified. It is necessary for the user to provide the information for the actual reactor being specified, which will allow the correct scaling to be performed. This is the purpose of variables CURSAT and FLXSAT .

One suggested way of determining values for CURSAT and FLXSAT from normal or dc magnetization curves (which seem to be more readily available than hysteresis loop curves) is as follows: beginning at the right of the normal magnetization curve, in its linear region, a straight-edge is used to extrapolate this line back to the left; the point where this straight line and the actual curve first begin to diverge is then taken as the saturation point.

Finally a caution seems in order. When determining the saturation point, care should be taken to determine it accurately since any error in determining CURSAT will cause a corresponding error in the width of the loop. For example, if the value of CURSAT was chosen to be a factor of ten too small (which might easily happen if one failed to notice a change of scale, for instance) the width of the loop at flux = 0 would also be a factor of ten too small. This is a fairly drastic error near zero flux, but quite possibly a relatively small error near the saturation region.

At this point, if it is desired to determine the hysteresis loop for a new hysteretic reactor, the user should specify new values for ITYPE, LEVEL, IPUNCH, CURSAT, and FLXSAT. A blank card will terminate hysteresis-curve requests. A second blank card is necessary to terminate all SATURATION cases and a third blank card terminates a nonexistent following data case.

Section 7.2b

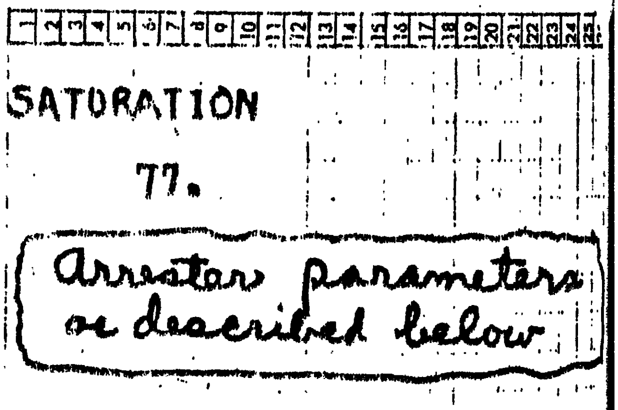
ARRDAT ------ A supporting routine designed to generate EMTP data parameters needed for the Section 1.32 modeling of multiphase ZnO surge arresters.

0. Overview; Access to Supporting Routine

Though in no way related to magnetic saturation, this little supporting program has been appended to the "SATURATION" overlay (number 42) for reasons of convenience. The code and user instructions which follow below were written by Dr. Vladimir Brandwajn of Ontario Hydro, supplied to BPA on cards as a self-contained program during April of 1980.

Application is to the multi-phase ZnO modeling of Section 1.32. There also is some applicability to SiC arresters, though dynamics of the gap will not be represented (unlike in Section 1.34). In summary, "ARRDAT" accepts manufacturer's data for the arrester as input, and calculates parameters that are required for the EMTP data cards of Section 1.32 (which are used to represent such arresters in EMTP simulations).

Access to "ARRDAT" is simple. Begin with a data card bearing the key word "SATURATION". Follow this with a second card having the request number FREQ = 77.0 (read as E8.0). See sketch at right. Control is then transferred to "ARRDAT", which reads further data as described by Vladimir.



Numerous cosmetic changes have been made to the Toronto code, in adding it to the EMTP. Thus, while the arithmetic should be unaffected, the format of printout may be somewhat different (e.g., one now sees interpreted data-card images as they are read). The user instructions have not yet been altered to reflect the new formats.

User's Instruction
for the Program
to Calculate the Parameters of Arresters

1. General

April 14, 1980

This program provides for a fit of exponential curves to a set of data points. The fitting is performed in the log-log plane and is non-iterative. The quality of the fit (the resulting fitting error) is a function of the input data and user's choice of number of exponential segments to be fitted. The fitting procedure minimizes the error in the least-squares sense.

2. Format of Data Cards

2.1 Card #1

NEXF	VREF	IPHASE	IMULT	IPRZNO
I12	E12.0	I12	I12	I12

NEXP-------Number of segments (different exponents) to be fitted. The choice of this number has to be made by the user. For ZnO and SiC, 2 exponents seem to provide an adequate fit, however a larger could be used if so required.* The maximum number allowed in the fitting program is 7.

VREF-------Reference voltage used to scale the voltage data points. The scaling is used to prevent a possible overflow during the simulation in the EMTP.

IPHASE------Number of phases of the multiphase compensation to be used in the EMTP. This number affects only the printed and punched output of the program. It can not, however, be left unspecified.

IMULT-------Minimum # of segments to appear in the output. This option allows the user, for example, to obtain punched cards for 2 exponential segments, as presently required by the EMTP, even if only one exponential segment was fitted. Defalut value, if unspecified, IMULT = 2.

IPRZNO-----Control of diagnostic printout. Suggested values 0 to 3. Amount of printout increases with the assigned values.

2.2 Card #2

A1	A2	A3	A4	A5	AMIN
E12.0	E12.0	E12.0	E12.0	E12.0	E12.0

A1------Voltage rating of the arrester upon which the input data are based in volts rms;

A2------The desired voltage rating of the arrester in volts rms. This variable can be used to:

a) Convert the arrester input data (voltages) from p.u. to V (volts);

b) Obtain the characteristic of an electrically similar arrester with a different voltage rating. The properties of similar arresters do not change with rating, providing a proportional number of blocks is used to obtain the new rating.

---

* At present, the EMTP assumes the maximum number of 2. This limitation, though not a very serious one, will be removed in the future.

c) If VREF is maintained proportional to A2, similar arresters will have identical parameters at all ratings.

A3------Multiplier used in the additional scaling of voltage points. It can be, for example, used to obtain a minimum characteristic (maximum energy) from a maximum characteristic (maximum voltage). The value to be normally used is 1.0.

A4------Current multiplier used in obtaining characteristics of arresters with # of columns different from that for which the data points are known. An even current distribution is assumed.

A5------Flag signalling to the program the existence (or its lack) of additional data describing the arrester before gap sparkover.

It permits the representation of:

a) arresters with shunt passive gaps. The shunted portion of the arrester can be of similar or dissimilar material;

b) arresters with series passive gap. Before gap sparkover, the arrester is inoperative. Therefore, this data specifies only the gap characteristic.

A5 =	0.0 or 1.0	no additional data, gapless arrester;
	0.0	additional data will be provided, indicating dissimilar material in a shunt gap or a series gap;
	1.0	reprocess the original input data after multiplying the voltag s by A5, similar material in an arrester with a shunt gap.

AMIN---Minimum value of current above which segment #1 of the arrester characteristic begins. Even if fitting a straight line passing through the origin, do not leave AMIN blank (zero), log 0.0 is not defined;

2.3 Cards Specifying Arrester Characteristic

These cards come in NEXP (see card #1) groups, each terminated by a blank card.

A	B
E12.0	E12.0

A-----Value of current (on the arrester characteristic) corresponding to:

B-----Value of th voltage

The user has to determine graphically the segments of the characteristic, thus establishing their number as well as their limits. This can be best done on the log-log paper. The following two groups of data cards are present if and only if the parameter A5 on the data card #2 was less than zero (A5<0).

2.4 Card #1

NEXP
I12

NEXP---Number of exponential segments to be fitted.

All the other constants are assumed to be as those specified on cards #1 & #2.

2.5 Cards Specifying the Arrester Characteristic

These cards are of the same form as those described in section 2.3.

2.6 Termination of Data Case

A blank card is used to terminate the execution. The user can, therefore, execute a number of data cases by providing additional data sequences as specified in sections 2.1 - 2.5. Each new case follows immediately the blank card terminating the data for the last segment of the previous case.

3.0 Examples

Consider a single-column ZnO arrester. The voltage points are known for an arrester rated 1 kV (crest), maximum voltage characteristic. The current points are given in A (crest). It is desired to obtain parameters for a 192 kV (rms), 3-column arrester with a maximum energy characteristic. The conversion factor to this characteristic is assumed to be .962. The arrester is equipped with a shunt gap and the shunted part is electrically similar to the rest of the arrester. The shunted part contains 12% additional blocks. A reference voltage 412500 V was chosen for the expected operating range of the 3-phase arrester.

3.1 Single-Exponent Fit

According to the data provided above, the following values are assigned to variables A1-A5;

A1 = 1.0/$\sqrt{2}$ th original rating of the arrester in kV (rms);

A2 = 192000. the required rating in V (rms)

A3 = .962 scaling factor for obtaining the desired maximum energy characteristic.

A4 = 3. the original data are given for a single-column arrester. Factor of 3.0 is needed to obtain the characteristic of a 3-column arrester.

A5 = 1.12 The arrester, before sparkover, contains 12% additional blocks.

A standard choice of AMIN is <u>.001A</u>, ie, somewhere at the end of the leakage current region.

3.2 Double Exponential Fit

The characteristic described above is now to be fitted with two exponentials. The border between the two segments has been determined (graphically) to lie between 100A and 200A.

3.3 Sample EMTP Input Data and Punched and Printed Output

Good news! Contrary to the advertised warning at the beginning of the section, I (WSM) have decided to be nice and provide current program input and output listings. The two preceding examples (Sections 3.1 and 3.2) are involved, though in reverse order, built into a single EMTP data case. The input data listing follows:

```
BEGIN NEW DATA CASE
SATURATION
     77.
           2      412500.              3            2           01
     .707107      192000.           .962          3.0         1.12          .001
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
         1.0         1.04
         2.0        1.055
         5.0         1.07
         10.         1.08
         20.         1.10
         50.        1.125
        100.         1.15
BLANK CARD ENDING CHARACTERISTIC.
        200.        1.182
        500.         1.24
       1000.        1.288
       2000.         1.35
       3000.         1.39
BLANK CARD ENDING CHARACTERISTIC.
           1      412500.              3            2           01
     .707107      192000.           .962          3.0         1.12          .001
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
         1.0         1.04
         2.0        1.055
         5.0         1.07
         10.         1.08
         20.         1.10
         50.        1.125
        100.         1.15
        200.        1.182
        500.         1.24
       1000.        1.288
       2000.         1.35
       3000.         1.39
BLANK CARD ENDING CHARACTERISTIC.
BLANK CARD ENDING FITTING CASES.
BLANK CARD ENDING ALL "SATURATION" CASES.
BEGIN NEW DATA CASE
BLANK CARD ENDING ALL EMTP DATA CASES.
```

As for output, it begins with the familiar interpreted input data cards, through the blank card which ends the second piece of the characteristic at 3000. amperes. Then internal printout which I have not bothered to study in detail begins. Finally, there is printout of the card images which should be written to the punch (LUNIT7 file) ----- cards which are to be used in some subsequent simulation as data belonging to a multi-phase ZnO arrester of Section 1.32 . After this, data input begins for the second example (the single-exponential fit). As it is somewhat redundant, only the first three lines of this output are displayed.

```
ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP), DIGITAL (DEC) VAX-11/780 TRANSLATION AS USED BY BPA IN PORTLAND, OREGON  97208
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS.)= 05/03/80  21.59.07  ANY PLOTS BEAR SAME FIGURES.                  VERSION # "M27." 
+F IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE 564-PAGE EMTP USER'S MANUAL DATED NOVEMBER, 1977.
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF   /LABEL/   EQUALS 200123  INTEGER WORDS.      703  1050  2500    30  9500
   125  6100  3000    50   300   100   140     5  9000   400     9     4    30  6000   500    72   200  3000     6  3700
--------------------------------------------------+--------------------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA | INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER
                                                  0         1         2         3         4         5         6         7
                                                  0         0         0         0         0         0         0         0
--------------------------------------------------+--------------------------------------------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.              |BEGIN NEW DATA CASE
REQUEST FOR MAGNETIC-SATURATION ROUTINE.          |SATURATION
FREQ=77 REQUESTS  ZNO  DATA GENERATOR.            |       77.
ARRESTER.    2.  0.413E+06     3     2     1      |          2      412500.          3           2          01
RATINGS.  0.71E+00  0.19E+06  0.96E+00  0.30E+01  |     .707107     192000.       .962          3.0        1.12        .001
COMMENT CARD.                                     |C 3456789012345678901234567890123456789012345678901234567890123456789012345678890
(I,V) POINT.     0.100000E+01    0.104000E+01 .   |           1.0        1.04
(I,V) POINT.     0.200000E+01    0.105500E+01     |           2.0        1.055
(I,V) POINT.     0.500000E+01    0.107000E+01     |           5.0        1.07
(I,V) POINT.     0.100000E+02    0.108000E+01     |           10.        1.08
(I,V) POINT.     0.200000E+02    0.110000E+01     |           20.        1.10
(I,V) POINT.     0.500000E+02    0.112500E+01     |           50.        1.125
(I,V) POINT.     0.100000E+03    0.115000E+01     |          100.        1.15
BLANK CARD ENDING (I,V) POINTS.                   |BLANK CARD ENDING CHARACTERISTIC.
(I,V) POINT.     0.200000E+03    0.118200E+01     |          200.        1.182
(I,V) POINT.     0.500000E+03    0.124000E+01     |          500.        1.24
(I,V) POINT.     0.100000E+04    0.128800E+01     |         1000.        1.288
(I,V) POINT.     0.200000E+04    0.135000E+01     |         2000.        1.35
(I,V) POINT.     0.300000E+04    0.139000E+01     |         3000.        1.39
BLANK CARD ENDING (I,V) POINTS.                   |BLANK CARD ENDING CHARACTERISTIC.

   **********  ERROR STATISTICS  **********
   SEGMENT              LOCAL ERROR            ACCUMULATED ERROR
       1            0.5838939740E-01           0.5838939740E-01
       2            0.4318787687E-02           0.6270818508E-01

  COMPARISON BETWEEN INPUT DATA AND THE RECALCULATED POINTS  &&&&&&&
        INPUT VOLTAGE          INPUT CURRENT     CALCULATED CURRENT
     0.2716592538E+06       0.3000000000E+01       0.3697707231E+01
     0.2755774161E+06       0.6000000000E+01       0.7198264878E+01
     0.2794958785E+06       0.1500000000E+02       0.1384330666E+02
     0.2821076887E+06       0.3000000000E+02       0.2131943048E+02
     0.2873319031E+06       0.6000000000E+02       0.4996815251E+02
     0.2938621736E+06       0.1500000000E+03       0.1418224270E+03
     0.3003924441E+06       0.3000000000E+03       0.3934037950E+03
     0.3087511904E+06       0.6000000000E+03       0.6480730609E+03
     0.3239014180E+0        0.1500000000E+04       0.1440748041E+04
     0.3364395374E+06       0.3000000000E+04       0.2714183329E+04
     0.3526346083E+06       0.6000000000E+04       0.5945550306E+04
     0.3630830412E+06       0.9000000000E+04       0.9675684428E+04

   REPROCESS INPUT DATA.  MULTIPLIER "AS" =    0.1120003000E+01
  INPUT DATA AFTER CONVERSION TO A LOG-LOG PLANE  ****************
                        CURRENT                      VOLTAGE
           0.477121254719662E+00     -0.132181428735580E+00
           0.778151250383644E+00     -0.125962306400649E+00
           0.117609125905568E+01     -0.119930988349151E+00
           0.147712125471966E+01     -0.115791010547411E+00
           0.177815125038364E+01     -0.107922080876136E+00
           0.217609125905568E+01     -0.980622435869794E-01
           0.247712125471966E+01     -0.881692588074908E-01
           0.277815125038364E+01     -0.768972894891241E-01
           0.317609125905568E+01     -0.557930808721256E-01
           0.347712125471966E+01     -0.392989030105674E-01
           0.377815125038364E+01     -0.188809875393546E-01
           0.395424250943932E+01     -0.619998678026859E-02

   **********  ERROR STATISTICS  **********
   SEGMENT              LOCAL ERROR            ACCUMULATED ERROR
       1            0.5838939740E-01           0.5838939740E-01
       2            0.4318787687E-02           0.6270818508E-01

  COMPARISON BETWEEN INPUT DATA AND THE RECALCULATED POINTS  &&&&&&&
        INPUT VOLTAGE          INPUT CURRENT     CALCULATED CURRENT
     0.3042383643E+06       0.3000000000E+01       0.3697707231E+01
     0.3086467061E+06       0.6000000000E+01       0.7198264878E+01
     0.3130350879E+06       0.1500000000E+02       0.1384330666E+02
     0.3159606091E+06       0.3000000000E+02       0.2131943048E+02
     0.3218117315E+06       0.6000000000E+02       0.4998815251E+02
     0.3291256165E+06       0.1500000000E+03       0.1418224270E+03
     0.3364395374E+06       0.3000000000E+03       0.3934037950E+03
```

```
 0.3438[illegible]E+04    0.5000000000E+03    0.4406730000E+05
 0.[illegible]E+05    0.1500000000E+04    0.1490745601E+05
 0.[illegible]E+05    0.3000000000E+04    0.2714383329E+04
 0.2349[illegible]E+06    0.6000000000E+04    0.3945553106E+04
 0.4082[illegible]E+06    0.9000000000E+04    0.5675634425E+04

 ***********  80-COLUMN CARD-IMAGE LISTING OF UNIT-7 PUNCHED CARDS.  --*
 ---------------------------------------------------------------------------------
         1         2         3         4         5         6         7         8
         0         0         0         0         0         0         0         0
 ---------------------------------------------------------------------------------

C RATING =192000.00  V-MULT =  0.96200E+00  I-MULT =  1.30000E+01  GAPPED
C 1PHASE     MULTIPLIER      EXPONENT        VMIN
       1  0.97385541E+09  0.46419997E+02  0.56495900E+00
       1  0.81268118E+05  0.16677590E+02  0.72923930E+00
     9999
       1  0.50558479E+07  0.46419997E+02  0.63275408E+00
       1  0.12276715E+05  0.16677590E+02  0.81674802E+00
     9999
       2  0.97385541E+09  0.46419997E+02  0.56495900E+00
       2  0.81269118E+05  0.16677590E+02  0.72923930E+00
     9999
       2  0.50558479E+07  0.46419997E+02  0.63275408E+00
       2  0.12276715E+05  0.16677590E+02  0.81674802E+00
     9999
       3  0.97385541E+09  0.46419997E+02  0.56495900E+00
       3  0.81268118E+05  0.16677590E+02  0.72923930E+00
     9999
       3  0.50558479E+07  0.46419997E+02  0.63275408E+00
       3  0.12276715E+05  0.16677590E+02  0.81674802E+00
     9999
 ---------------------------------------------------------------------------------

ARRESTER,     1    0.413E+06     3     2     1     1       1       412800.         3          3          01
RATINGS,  0.71E+00  0.19E+06  0.96E+00  0.30E+01  1    .707107   192000.      .962        3.0       1.12       .001
COMMENT CARD,                                   1C 3456789012345678901234567890123456789012345678901234567890
```

Finally, consider the way execution of this routine ends. Shown below is the very end of the LUNIT7 listing for the final (second) example which was buried in the data case. After two blank cards, the familiar summary statistics of data-case termination app ar:

```
       3  0.59605704E+06  0.26530762E+02  0.46665235E+00
     9999
       3  0.29479544E+05  0.26530762E+02  0.54905054E+00
       3  0.29479544E+05  0.26530762E+02  0.54905054E+00
     9999
 ---------------------------------------------------------------------------------

BLANK CARD ENDS ARRESTER CASES.                      BLANK CARD ENDING FITTING CASES.
BLANK CARD TERMINATING ALL SATURATION CASES.         BLANK CARD ENDING ALL "SATURATION" CASES.

CORE STORAGE FIGURES FOR PRECEDING DATA CASE NOW COMPLETED.  ----------------------------  PRESENT    PROGRAM
A VALUE OF  -9999 INDICATES DEFAULT, WITH NO FIGURE AVAILABLE.                              FIGURE      LIMIT (NAME)
    SIZE LIST 1.   NUMBER OF NETWORK NODES.                                                  -9999        703 (LBUS)
    SIZE LIST 2.   NUMBER OF NETWORK BRANCHES.                                               -9999       1050 (LBRNCH)
    SIZE LIST 3.   NUMBER OF DATA VALUES IN R, L, C TABLES.                                  -9999       2500 (LDATA)
    SIZE LIST 4.   NUMBER OF ENTRIES IN SOURCE TABLE.                                        -9999         30 (LEXCT)
    SIZE LIST 5.   STORAGE FOR  (YBA/YBB)  PLUS FACTORED  (YAA/YBB?) ]                      -9999       9500 (LYMAT)
    SIZE LIST 6.   NUMBER OF ENTRIES IN SWITCH TABLE.                                        -9999        125 (LSWTCH)
    SIZE LIST 7.   NUMBER OF NONZERO ENTRIES IN REDUCED MATRIX (YBB/YBB?).                   -9999       8100 (LSMAT)
    SIZE LIST 8.   NUMBER OF PAST HISTORY POINTS FOR DISTRIBUTED LINES.                      -9999       3000 (LPAST)
    SIZE LIST 9.   NUMBER OF NONLINEAR ELEMENTS.                                             -9999         50 (LNONL)
    SIZE LIST 10.  NUMBER OF POINTS DEFINING NONLINEAR CHARACTERISTICS.                      -9999        300 (LCHAR)
    SIZE LIST 11.  NUMBER OF BRANCH OR SELECTIVE-NODE-VOLTAGE OUTPUTS.                       -9999        100 (NTOUT)
    SIZE LIST 12.  NUMBER OF OUTPUT QUANTITIES (LIMITED ONLY WHEN PRINTING MAX ABSOLUTE VALUES). -9999    140 (LPEAK)
    SIZE LIST 13.  NUMBER OF "WEIGHTING" FREQUENCY-DEPENDENT LINE MODES.                     -9999          5 (LFDEP)
    SIZE LIST 14.  NUMBER OF CELLS USED TO STORE FREQ.-DEPENDENCE WEIGHTING FUNCTIONS.       -9999       9000 (LWT)
    SIZE LIST 15.  NUMBER OF CELLS USED FOR EXPONENTIAL-TAIL LINE-HISTORY STORAGE.           -9999        400 (LTAILS)
    SIZE LIST 16.  NUMBER OF SWITCHES BEARING CODE NAME "PART ENTER".                        -9999          8 (LLUMP)
    SIZE LIST 17.  NUMBER OF DYNAMIC SYNCHRONOUS MACHINES.                                   -9999          4 (LSYN)
    SIZE LIST 18.  NUMBER OF BRANCH POWER-AND-ENERGY OUTPUTS.                                -9999         30 (MAXPE)
    SIZE LIST 19.  FLOATING-POINT WORKING SPACE FOR ALL TACS ARRAYS.                         -9999       6000 (LTACST)
    SIZE LIST 20.  RECURSIVE CONVOLUTION PARAMETER STORAGE FOR NON-COPIED BRANCH COMPONENTS. -9999        500 (LFSEM)
    SIZE LIST 21.  TOTAL STORAGE CELLS FOR SEMLYEN/AMETANI TRANSFORMATION MATRICES.          -9999         72 (LFD)
    SIZE LIST 22.  NUMBER OF CELLS FOR AMETANI/SEMLYEN CONVOLUTION HISTORY.                  -9999        200 (LHIST)
    SIZE LIST 23.  GIANT ARRAYS FOR RENUMBERING AND STEADY-STATE SOLUTION CALCULATIONS.      -9999       3000 (LSIZ23)
    SIZE LIST 24.  NUMBER OF PHASES OF COMPENSATION, BASED ON MAXIMUM NODES.                 -9999   [illegible] (NCOMP)
    SIZE LIST 25.  FLOATING-POINT WORKING SPACE FOR U.M. ARRAYS.                             -9999       3100 (LSPCUM)
TIMING FIGURES (DECIMAL) CHARACTERIZING CASE SOLUTION SPEED.  ----------------------------  CP SEC    I/O SEC    SU
                                                                               TOTALS       6.490     0.000     1.4
```

To conclude the illustrative documentation, I display a listing of the card images which were written on the LUNIT7 file. Note that there really are two unrelated groupings, corresponding to the two subcases that were buried in the EMTP data case:

```
C RATING =192000.00  V-MULT =  0.96200E+00  I-MULT =  0.30000E+01  GAPPED
C IPHASE        MULTIPLIER        EXPONENT            VMIN
         1  0.97385541E+09  0.46419997E+02  0.56495900E+00
         1  0.81268118E+05  0.16677590E+02  0.72923930E+00
             9999
         1  0.50558479E+07  0.46419997E+02  0.63275408E+00
         1  0.12276715E+05  0.16677590E+02  0.81674802E+00
             9999
         2  0.97385541E+09  0.46419997E+02  0.56495900E+00
         2  0.81268118E+05  0.16677590E+02  0.72923930E+00
             9999
         2  0.50558479E+07  0.46419997E+02  0.63275408E+00
         2  0.12276715E+05  0.16677590E+02  0.81674802E+00
             9999
         3  0.97385541E+09  0.46419997E+02  0.56495900E+00
         3  0.81268118E+05  0.16677590E+02  0.72923930E+00
             9999
         3  0.50558479E+07  0.46419997E+02  0.63275408E+00
         3  0.12276715E+05  0.16677590E+02  0.81674802E+00
             9999
C RATING =192000.00  V-MULT =  0.96200E+00  I-MULT =  0.30000E+01  GAPPED
C IPHASE        MULTIPLIER        EXPONENT            VMIN
         1  0.59605704E+06  0.26530262E+02  0.48665235E+00
         1  0.59605704E+06  0.26530262E+02  0.48665235E+00
             9999
         1  0.29479544E+05  0.26530262E+02  0.54505064E+00
         1  0.29479544E+05  0.26530262E+02  0.54505064E+00
             9999
         2  0.59605704E+06  0.26530262E+02  0.48665235E+00
         2  0.59605704E+06  0.26530262E+02  0.48665235E+00
             9999
         2  0.29479544E+05  0.26530262E+02  0.54505064E+00
         2  0.29479544E+05  0.26530262E+02  0.54505064E+00
             9999
         3  0.59605704E+06  0.26530262E+02  0.48665235E+00
         3  0.59605704E+06  0.26530262E+02  0.48665235E+00
             9999
         3  0.29479544E+05  0.26530262E+02  0.54505064E+00
         3  0.29479544E+05  0.26530262E+02  0.54505064E+00
             9999
```

WEIGHT —— A supporting program used to calculate weighting functions $a_1(t)$ and $a_2(t)$ for use in the BPA Electromagnetic Transients Program.

PURPOSE

As per Section 1.26b of the EMTP User's Manual, the frequency-dependent-line feature requires knowledge of certain weighting functions $a_1(t)$ and $a_2(t)$ for a mode (generally the zero-sequence mode only) of the transmission line. Program WEIGHT reads in the frequency-dependent line constants ($R(f_i)$, $L(f_i)$, f_i) , calculates the necessary weighting functions, and then punches the results on cards which can be directly read in by the transients program.

At the present time, frequency dependence is only used for the zero-sequence (earth-return) mode, further assuming reasonable ground resistivity. Reliability of the logic of WEIGHT for other situations is questionable, and would require modifications for such use.

For given line geometry, length, and ground resistivity, the calculation of weighting functions $a_1(t)$ and $a_2(t)$ needs be performed only once. Program WEIGHT is thus used to build a card file of weighting functions for lines under study.

MATHEMATICAL THEORY

The calculation of weighting functions from the inputted line constants is done by inverse Fourier transformation, as described in Ref. 3 of the Transients Program User's Manual. See that paper for an explanation of terms and procedures involved.

INPUT DATA FORMAT

For each line to be processed, two cards of miscellaneous data parameters must precede the cards defining the frequency dependence of R and L , which are in turn terminated by a blank card. An extra blank card is required at the end of all such data sets, to turn the program off.

First, consider the format and meaning of the two miscellaneous data cards of "WEIGHTING" :

DIST	CAP	WMAX	RMAX	HZINF	DTRAT	FRAT	AXIS
E8.0	E8.0	E8.0	E8.0	E8.0	E8.0	E8.0	E8.0

NPOINT	MNUM	NSCALE	NPINF	IPUNCH	ITAIL	MPLOT	MCAT
I8	I8	I8	I8	I8	I8	I8	I8

The first two parameters ("DIST" and "CAP") are related to line geometry and other physical factors; they must be punched nonzero, unless "LINE CONSTANTS" or "CABLE CONSTANTS" data is embedded within the "WEIGHTING" data case, as shall be described later. These two parameters are:

DIST ～ Length of line (in units consistent with R and L).

CAP ～ Mode capacitance (in microfarads / unit length).

All other fields can be left blank, if default values are acceptable. The default values shown below in parentheses will be used in such a case. Meaning of the remaining parameters is as follows:

WMAX (4) ～ The inverse Fourier transform integral over $\int_0^\infty \cdots d\omega$ is truncated numerically to $\int_0^\Omega \cdots d\omega$ where Ω = WMAX·40/τ.

RMAX (5) ～ The number of travel times of the line over which the weighting functions are to be computed.

HZINF (6000000) ～ The maximum frequency in Hz used for inverse Fourier transformation on the infinite line (to produce $a_2(t)$ for $t < \tau$).

DTRAT (4) ～ The factor by which we periodically increase Δt during the inverse Fourier transformation on the infinite line. Mnemonically, the "dt ratio".

FRAT (.2) ～ Over the frequency range $[0, 5 \cdot \text{DELW}]$, we integrate with variable step size $\Delta\omega$ equal to FRAT times the frequency increment of the defining line constants around the value in question. Here DELW is the uniform step width used for the rest of the integration (equal to WMAX 40/τ /NPOINT).

AXIS ～ Field used only if the user wants plotted output. See later section.

NPOINT (2000) ～ The number of points on the frequency axis used for our integration (not counting the special treatment using variable step size near zero frequency).

MNUM (50) — The finite-line response for $t > \tau$ is calculated at regular time increments Δt, where $\Delta t = \tau / MNUM$ (τ = travel time of the line at infinite frequency).

NSCALE (10) — The number of times that Δt is periodically increased by factor DTRAT when working on the infinite-line response.

NPINF (100) — The total number of time points calculated for the infinite line. These points are used for $a_2(t)$ over the range $0 < t < \tau$.

IPUNCH (0) — A control parameter for punched-card output of the weighting functions $a_1(t)$ and $a_2(t)$.

$$\begin{cases} 0 \Rightarrow \text{yes, punch the deck} \\ 1 \Rightarrow \text{no punching.} \end{cases}$$

ITAIL (0) — A flag which indicates whether or not a "tail correction" to the weighting functions is desired:

$$\begin{cases} 0 \Rightarrow \text{No tail correction} \\ 1 \Rightarrow \text{Yes, correct the tails} \end{cases}$$

The tail-correction process scales the tails of $a_1(t)$ and $a_2(t)$ so that the total area under each weighting function will exactly equal the known theoretical limit which is given in equation (12) of Reference 3. Whether this is really an improvement is debatable. The resulting weighting functions will be discontinuous at the point where the tail begins. At present (July, 1977), this is just an experimental idea which is being evaluated for short lines (typically 10 miles) which otherwise have problems. This tail-correction usage is not recommended for general use at this time, and certainly not for the inexperienced user.

MPLOT, **MCAT** } Fields employed only if plotted output is desired. See later section.

After the above two miscellaneous data cards, an indeterminate number of line constants cards are to appear. Terminated by a blank card, these are to have the following format, and are to appear in order of increasing frequency:

1–16	17–32	33–48
R [Ω/length]	L [mH/length]	f [Hz]
E16.0	E16.0	E16.0

R —— Modal resistance, in ohms per unit length (consistent with "DIST");

L —— Modal inductance, in millihenries per unit length;

f —— Frequency in Hertz.

As for the input of line constants, several points deserve mention:

1. Resistance R is in units of [ohm/length], while inductance L is in units of [mH/length]. The units for length must of course agree with what is used for variable DIST (columns 1-8 of the first data card). Frequency f is in units of [Hz].

2. Cards must be inputted in order of increasing frequencies f_i.

3. Logarithmic (geometric) spacing of the frequency points f_i is generally most convenient, with 4 points per decade (giving rise to points like 1.0, 1.78, 3.16, 5.62, 10.0, etc.) being typical. Starting at $f_1 = 0.1$ Hz and going through final frequency $f_n = 10^7$ Hz then would require 33 points (33 input cards). Such spacing is recommended for normal production runs.

4. The frequency span of the line constants should cover both the frequencies "HZINF" and WMAX * 40 / TAU , where "TAU" is the travel time of the mode. As a crude general calculation, remember that at the speed of light, each mile of line contributes about 5.0 microseconds to the travel time. The speed of light is 186 miles/msec or 300 KM/msec). For moderate-length or long lines (say 50 miles or long r), "HZINF" will be the larger of the two just-cited frequencies, note. But be very careful of short lines, since as the line length goes to zero, the frequency span must become infinite ---- and the weighting function $a_1(t)$ becomes a Dirac impulse function. As for the beginning frequency, 0.01 or 0.1 Hz is typically used.

Sample EMTP Output for "WEIGHTING" Data Case

Consider the derivation of weighting functions $a_1(t)$ and $a_2(t)$ for the zero-sequence mode of a high voltage overhead line (500 kV?) which is 34.5 miles long. This is the situation of UTPF Test Case #41, the partial output of which shall now be described. Note in the listing below that default parameters (miscellaneous data constant values) were used, which is the typical usage for the zero sequence mode of lines that are perhaps 50 or more miles long.

Line printer output for the "WEIGHTING" data case begins with an interpreted listing of all input data cards, since the inverse Fourier transformation can not be begun until all data is known. We have:

```
--------------------------------------------------+------------------------------------------------------------------------
IPTIVE INTERPRETATION OF NEW-CASE INPUT DATA     | INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER.
                                                  0        1         2         3         4         5         6         7         8
                                                  0        0         0         0         0         0         0         0         0
--------------------------------------------------+------------------------------------------------------------------------
R CARD PRECEDING NEW DATA CASE.                   |BEGIN NEW DATA CASE
NT CARD.                                          |C        UTPF TEST CASE NO. 41
NT CARD.                                          |C        TEST OF WEIGHTING-FUNCTION SUPPORTING PROGRAM, WHICH CALCULATES
NT CARD.                                          |C        WEIGHTING FUNCTIONS A1(T)  AND  A2(T)  FOR THE ZERO-SEQUENCE OF
NT CARD.                                          |C        DISTRIBUTED-PARAMETER LINES HAVING FREQUENCY-DEPENDENT LINE CONSTANTS.
T FOR WEIGHTING-FUNCTION ROUTINE.                 |WEIGHTING ------------ key-word card
 DATA.     .3450E+02    .1210E-01    -.0          |   34.5   .01210  } miscellaneous data cards
MISC.    -0      -0      -0      -0      -0      -0 |
 CONST.  R,L,F.    .310E-01    .865E+01    .100E+00 |   3.09760000E-02    8.65400000E+00    1.00000000E-01  ⎫
 CONST.  R,L,F.    .316E-01    .844E+01    .237E+00 |   3.16670000E-02    8.43870000E+00    2.37137000E-01  ⎪
 CONST.  R,L,F.    .325E-01    .816E+01    .422E+00 |   3.25020000E-02    8.16150000E+00    4.21697000E-01  ⎪ line
 CONST.  R,L,F.    .341E-01    .788E+01    .750E+00 |   3.40550000E-02    7.88400000E+00    7.49894000E-01  ⎬
 CONST.  R,L,F.    .352E-01    .775E+01    .100E+01 |   3.52170000E-02    7.74620000E+00    1.00000000E+00  ⎪ constants
 CONST.  R,L,F.    .417E-01    .733E+01    .237E+01 |   4.17000000E-02    7.33180000E+00    2.37137000E+00  ⎪
 CONST.  R,L,F.    .604E-01    .706E+01    .422E+01 |   6.03610000E-02    7.05674000E+00    4.21697000E+00  ⎭
```

— cont. —

— cont. —

```
 R,L,F.   .657E-01   .670E+01   .750E+01  |  6.5691000E-02   6.7016000E+00   7.4989400E+00
 R,L,F.   .773E-01   .665E+01   .100E+02  |  7.7321000E-02   6.6465000E+00   1.0000000E+01
 R,L,F.   .141E+00   .624E+01   .237E+02  |  1.4067000E-01   6.2351000E+00   2.3713700E+01
 R,L,F.   .225E+00   .596E+01   .422E+02  |  2.2493000E-01   5.9645000E+00   4.2169700E+01
 R,L,F.   .373E+00   .570E+01   .750E+02  |  3.7326000E-01   5.6962000E+00   7.4989400E+01
 R,L,F.   .405E+00   .556E+01   .100E+03  |  4.0527000E-01   5.5632000E+00   1.0000000E+02
 R,L,F.   .101E+01   .517E+01   .237E+03  |  1.0061000E+00   5.1699000E+00   2.3713700E+02
 R,L,F.   .186E+01   .491E+01   .422E+03  |  1.8623000E+00   4.9140000E+00   4.2169700E+02
 R,L,F.   .318E+01   .466E+01   .750E+03  |  3.1776000E+00   4.6648000E+00   7.4989400E+02
 R,L,F.   .414E+01   .454E+01   .100E+04  |  4.1410000E+00   4.5433000E+00   1.0000000E+03
 R,L,F.   .905E+01   .419E+01   .237E+04  |  9.0494000E+00   4.1938000E+00   2.3713700E+03
 R,L,F.   .150E+02   .398E+01   .422E+04  |  1.5010000E+01   3.9765000E+00   4.2169700E+03
 R,L,F.   .249E+02   .377E+01   .750E+04  |  2.4947000E+01   3.7746000E+00   7.4989400E+03
 R,L,F.   .312E+02   .368E+01   .100E+05  |  3.1194000E+01   3.6802000E+00   1.0000000E+04
 R,L,F.   .622E+02   .343E+01   .237E+05  |  6.2205000E+01   3.4264000E+00   2.3713700E+04
 R,L,F.   .960E+02   .328E+01   .422E+05  |  9.6012000E+01   3.2837000E+00   4.2169700E+04
 R,L,F.   .145E+03   .316E+01   .750E+05  |  1.4497000E+02   3.1628000E+00   7.4989400E+04
 R,L,F.   .177E+03   .311E+01   .100E+06  |  1.7689000E+02   3.1105000E+00   1.0000000E+05
 R,L,F.   .310E+03   .298E+01   .237E+06  |  3.1018000E+02   2.9834000E+00   2.3713700E+05
 R,L,F.   .441E+03   .292E+01   .422E+06  |  4.4116000E+02   2.9204000E+00   4.2169700E+05
 R,L,F.   .610E+03   .287E+01   .750E+06  |  6.1022000E+02   2.8718000E+00   7.4989400E+05
 R,L,F.   .728E+03   .285E+01   .100E+07  |  7.2844000E+02   2.8520000E+00   1.0000000E+06
 R,L,F.   .117E+04   .281E+01   .237E+07  |  1.1745000E+03   2.8066000E+00   2.3713700E+06
 R,L,F.   .160E+04   .279E+01   .422E+07  |  1.6001000E+03   2.7853000E+00   4.2169700E+06
 R,L,F.   .217E+04   .277E+01   .750E+07  |  2.1684000E+03   2.7693000E+00   7.4989400E+06
 R,L,F.   .252E+04   .276E+01   .100E+08  |  2.5202000E+03   2.7629000E+00   1.0000000E+07
BLANK CARD TERMINATING LINE CONSTANTS  R, L, F .  |
```

R_i, L_i, f_i for zero-sequence mode

— blank termination

Next, after printout of the infinite-frequency characteristic impedance "Z1" and the infinite-frequency travel time "TAU", there will be "NSCALE" (equal to default value 5) short outputs which document the $a_2(t)$ calculation for the infinite line. Shown below is the first of these, plus the beginning of the second:

t_i $\quad$ $a_i(t_i)$ $\quad$ $\int_0^{t_i} a_i(\tau)\,d\tau$

```
Z1=   477.4461              TAU= .0001994777

 T MICROSEC      (Z-Z1)/(Z+Z1)        AREA
                                                   BOUND         AREA  U*A2(U)
      .0000      144111.636161      .000000       .000000        .0
      .0279      131425.470439      .003830       .003661        .509945E-10
      .0557      101521.963194      .007082       .006489        .100767E-09
      .0836       77052.712452      .009514       .008524        .344570E-09
      .1114       57757.015651      .011316       .010135        .519294E-09
      .1393       51380.312629      .012884       .011620        .712434E-09
      .1671       50681.119596      .014333       .013052        .933970E-09
      .1950       44746.566466      .015662       .014278        .117348E-08
      .2228       38106.413636      .016816       .015340        .141320E-08
      .2507       34757.023152      .017831       .016308        .165291E-08
      .2786       34407.395491      .018794       .017266        .190775E-08
      .3064       33707.141686      .019743       .018205        .218510E-08
      .3343       31057.365044      .020665       .019070        .247155E-08
      .3621       28169.213177      .021470       .019855        .276023E-08
      .3900       26997.031619      .022218       .020607        .304496E-08
      .4178       27022.416770      .022991       .021360        .335286E-08
      .4457       26418.241917      .023715       .022096        .367413E-08
      .4736       24829.630179      .024449       .022787        .400109E-08
      .5014       23649.449261      .025124       .023466        .433062E-08
      .5293       23748.175089      .025784       .024188        .467105E-08
      .5571       24173.186914      .026492       .024781        .501369E-08
      .5850       21562.323859      .027116       .025437        .541124E-08

 T MICROSEC      (Z-Z1)/(Z+Z1)
                                      AREA
                                                   BOUND
                                                                 AREA  U*A2(U)
      .5850  *    23562.032389      .027116       .025437        .541124E-08
      .6964       20198.624209      .029954       .027888        .696481E-08
      .8078       17137.830610      .031634       .029598        .851979E-08
      .9193       14962.080921      .033423       .031265        .100574E-07
     1.0307       13941.573767      .035033       .032817        .116237E-07
     1.1421
```

⋮ Etc.

Next there is a tabulation which documents $a_1(t)$ and $a_2(t)$ for the finite line. This begins at a time which is just less than the infinite-frequency travel time "TAU", and it extends through a time which is equal to "TMAX" (equal to default value 5.0 here) travel times. The beginning of such output follows:

Etc.

```
        176.8842            126.666876             .142686             .136748          .399790E-05
        185.2154            118.028557             .143561             .137586          .415880E-05
        192.3465            115.535999             .144397             .138398          .431492E-05

     T MMSEC         A1(T)          A2(T)          AREA A1        AREA A2       UAREA1         UAREA2       ROW
    192.3465    .148772E+02    .115314E+03     .00000000     .14459773     .0            .43145E-05      1
    196.3361   -.648489E+02    .111187E+03    -.00009968     .14484895    -.19899E-07    .44823E-05      2
    200.3256   -.170831E+03    .106770E+03    -.00056981     .14520771    -.11335E-06    .44893E-05      3
    204.3152    .363678E+03    .104564E+03    -.00018912     .14571386    -.33395E-07    .45754E-05      4
    208.3048    .393862E+04    .102821E+03     .00838104     .14612536     .17441E-05    .45684E-05      5
    212.2943    .104336E+05    .983450E+02     .03689837     .14632584     .77997E-05    .47444E-05      6
    216.2839    .160298E+05    .979516E+02     .08942283     .14671442     .19136E-04    .48283E-05      7
    220.2734    .186377E+05    .956281E+02     .15897943     .14730439     .34299E-04    .49139E-05      8
    224.2630    .187923E+05    .965244E+02     .23364115     .14768989     .58835E-04    .49987E-05      9
    228.2525    .176277E+05    .947267E+02     .30629118     .14807159     .57264E-04    .50859E-05     10
    232.2421    .159476E+05    .936319E+02     .37326636     .14844733     .92663E-04    .51719E-05     11
    236.2316    .141101E+05    .910383E+02     .43324871     .14881570     .96723E-04    .52578E-05     12
    240.2212    .123179E+05    .893574E+02     .48597477     .14917994     .10920E-03    .53435E-05     13
    244.2107    .106833E+05    .874451E+02     .53185664     .14953829     .12139E-03    .54290E-05     14
    248.2003    .924167E+04    .860857E+02     .57186184     .14987494     .13019E-03    .55142E-05     15
    252.1898    .887099E+04    .838767E+02     .60829654     .15021358     .13886E-03    .55990E-05     16
    256.1794    .788483E+04    .824452E+02     .63636447     .15054926     .14648E-03    .56833E-05     17
    260.1690    .685214E+04    .811751E+02     .66239924     .15087175     .15320E-03    .57676E-05     18
    264.1585    .522818E+04    .806785E+02     .68490896     .15119559     .15989E-03    .58523E-05     19
    268.1481    .455249E+04    .801743E+02     .70441128     .15151544     .16420E-03    .59376E-05     20
```

Etc.

The end of this just-described output is followed by a message which shows the total area under the two weighting function curves. This figure should theoretically be unity, with the error of .003 (see below) being typical. Then comes documentation of the weighting function cards which can be punched for the user (should he set "IPUNCH" equal to zero). Only the beginning of these records is shown:

Etc.

```
    978.2887    .585236E+02   -.416196E+02     .97221687     .03841539     .28752E-03   -.65561E-04    198
    982.2783    .579893E+02   -.413256E+02     .97249912     .03824953     .28775E-03   -.65724E-04    199
    986.2678    .574029E+02   -.409659E+02     .97272915     .03808536     .28797E-03   -.65885E-04    200

DONE WITH WEIGHTING-FUNCTION DERIVATION BY INVERSE FOURIER TRANSFORMATION.   THE TOTAL AREA UNDER THE TWO
WEIGHTING FUNCTION CURVES JUST DERIVED IS   1.00261 ,   WHICH SHOULD BE CLOSE TO THE THEORETICAL LIMIT OF
UNITY.   NOW WHEN THE WEIGHTING FUNCTIONS ARE READ BACK INTO THE T.P. AS PART OF A T.P. DATA CASE TO BE SOLVED,
A SIMILAR AREA FIGURE WILL BE FOUND AS PART OF THE T.P. RECORD INTERPRETATION FOR THE FINAL WEIGHTING-FUNCTION CARD.
THESE TWO AREAS SHOULD BE VERY CLOSE, DIFFERING ONLY IN THAT THE ABOVE-PRINTED FIGURE INCLUDES "NOISE" OF
A1(T)   WHICH PRECEDES THE RISE OF THIS FUNCTION THROUGH ZERO TO ITS POSITIVE PEAK.   THIS NOISE WILL BE ZEROED
BEFORE PUNCHING OUT THE WEIGHTING FUNCTIONS ON CARDS, THEREBY CHANGING THE AREA OF THE RESULTING CURVE VERY SLIGHTLY.

    NTIME1    NTIME2    LOCMAX    LOCMIN        T1
      201       305        73       251   471.9981

201 T(I), A(I), POINTS---FAR-END (FORWARD) WEIGHTING FUNCTION
   192.3465       .00   196.3361       .00   200.3256       .00   204.3152    363.68
   208.3048   3938.62   212.2943  10433.56   216.2839  16029.77   220.2734  18637.66
   224.2630  18792.34   228.2525  17627.75   232.2421  15947.56   236.2316  14110.13
   240.2212  12317.94   244.2107  10683.26   248.2003   9241.67   252.1898   8870.99
   256.1794   7884.83   260.1690   6852.14   264.1585   5228.18   268.1481   4552.49
   272.1376   4037.62   276.1272   3659.41   280.1167   3367.19   284.1063   3119.32
   288.0958   2892.98   292.0854   2675.37   296.0749   2466.59   300.0645   2268.31
```

Etc.

Finally, the end of such card-image documentation of $a_1(t)$ and $a_2(t)$ will be followed by an EMTP-interpreted blank card from the user's input data deck. This will be the case if only a single inverse Fourier transformation operation was to be performed within "WEIGHTING". This blank card signals the end of such "WEIGHTING" data cases, and serves to transfer control from "WEIGHTING" back to the solution overlays of the EMTP. An arbitrary EMTP data case could be solved next. In this case, we want to stop execution (assuming that only this one test problem was to be solved), which can be accomplished by means of a blank first card of the following data case (as per Section 1.0b):

• Etc.

```
.14.6836   -159.60  938.4983   -157.52  942.3687   -156.16  946.8721   -154.87
.51.3416   -153.13  954.3614   -151.63  958.3489   -150.42  962.3365   -149.08
 6.3400    -147.88  970.3096   -146.32  974.2991   -144.69  978.2887   -143.19
 82.2783   -141.95
 K CARD TERMINATING ALL  "WEIGHTING"  CASES.   |

 CTROMAGNETIC TRANSIENTS PROGRAM (EMTP), CDC TRANSLATION PRODUCED BY THE BONNEVILLE POWER ADMINISTRATION, PORTLAND,
 GON.    DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) =  07/29/77  08.55.18    ANY PLOTS BEAR THE SAME FIGURES.
 IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE 259-PAGE EMTP USER'S MANUAL DATED JANUARY, 1974.
 EPENDENT LIST LIMITS FOLLOW,   TOTAL LENGTH OF   /LABEL/   EQUALS  8183  INTEGER WORDS.
 30     50   300   180   500    30   500   400   15    30    50   60    5   600   90    4    8    8    1   48   100   100
 ------------------------------------------------------------------------------------------------------------------------
 CRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA | INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER.
                                                0         1         2         3         4         5         6         7         8
                                                0         0         0         0         0         0         0         0         0
 ------------------------------------------------------------------------------------------------------------------------
 NLK CARD PRECEDING NEW DATA CASE.              |BEGIN NEW DATA CASE
 UN TERMINATION-OF-RUN CARD.                    |
```

Use of "WEIGHTING" along with "LINE CONSTANTS" or "CABLE CONSTANTS"

The input and output as described above is applicable to the original mode of "WEIGHTING" usage, before "LINE CONSTANTS" or "CABLE CONSTANTS" were available within the EMTP. The original mode of usage is somewhat inconvenient in that the user must supply R and L as a function of frequency ---- quantities which he may not have immediately available.

Most users now prefer to start with the geometrical characterization of the line, and derive weighting functions $a_1(t)$ and $a_2(t)$ in a single step. This is possible, using an internal program transfer between "WEIGHTING" and either "LINE CONSTANTS" or "CABLE CONSTANTS". The format to be followed is summarized by the following:

a) Be nice, and start with a "BEGIN NEW DATA CASE" card, as per Section 1.0a .

b) Then come the data cards for a complete "LINE CONSTANTS" or "CABLE CONSTANTS" calculation (see Section 7.4 or 7.7, respectively). There should be exactly three frequency cards as part of this data grouping:

   1. First, there is to be one frequency card for a near-dc frequency. For high-precision computation (e.g., 64-bit IBM floating-point), f = 1.E-3 Hz can be used without any apparent numerical difficulty. Experience with lower-precision machines is not available at this time. Even 0.1 Hz or 1.0 Hz is quite acceptable, since the only use of the resulting line constants is for estimation of the dc resistance of the line, for possible use with the tail-correction option (see data parameter "IFTAIL").

   2. 2nd, there is to be one frequency card for the steady-state frequency at which the resulting line model is to be used. This is usually 50 Hz or 60 Hz for ac systems. For dc systems, use some small value such as 0.1 Hz . See further comment about this below.

   3. Third (after the just-listed card), there is to be one frequency card which requests the logarithmic looping over all frequencies which are required by the inverse Fourier transformation of "WEIGHTING". Typically this will provide for four or five points per decade, beginning at 0.1 Hz and ending at 1.E+7 Hz .

c) Then come the two miscellaneous data cards of "WEIGHTING" , as previously documented. Modal capacitance "CAP" can be left blank.

d) Next comes one blank card, which serves to turn off "WEIGHTING" , and transfer control back to the EMTP solution overlays.

e) Finally, a "BEGIN NEW DATA CASE" card, followed by a blank card, will terminate the run (stop the computer job).

As an example of a data deck which has been constructed according to these rules, consider the following:

```
0        1         2         3         4         5         6         7         8
0        0         0         0         0         0         0         0         0
--------------------------------------------------------------------------------
BEGIN NEW DATA CASE
C     UTPF TEST CASE NO. 101
WEIGHTING
LINE CONSTANTS
C     JOHN DAY LOWER MONUMENTAL    500  KV LINE ... M-3 TOWER
  1 .364     .06 4              1.602      .00     80.0    35.0                 A1
  1 .364     .06 4              1.602     1.50     80.0    35.0                 A2
  2 .364     .06 4              1.602    20.00    107.5    62.5                 B1
  2 .364     .06 4              1.602    21.50    107.5    62.5                 B2
  3 .364     .06 4              1.602    40.00     80.0    35.0                 C1
  3  364     .06 4              1.602    41.50     80.0    35.0                 C2
  0   .5    2.61 4               .386     7.85    128.5   113.0                 TERRA1
  0   .5    2.61 4               .386    33.65    128.5   113.0                 TERRA2
       Blank card ending conductor cards
    100.     .0001       1
    100      60.         1                                     1         88
    100       .1         1                                     1         88
                                                               1    8    4 88
                   Blank card ending frequency cards
                   Blank card ending "LINE CONSTANTS" cases.
    138.
                   Blank integer miscellaneous data card of "WEIGHTING".
                   Blank card ending "WEIGHTING" cases.
```

This data case was used to derive weighting functions $a_1(t)$ and $a_2(t)$ for the zero-sequence mode of the 138-mile 500-kV BPA ac line which connects "John Day" with "Lower Monumental" . Several specific details are perhaps worthy of mention:

<u>Detail 1</u> : Be careful of the blank cards which finish the "LINE CONSTANTS" data. Note that there are exactly two such cards : one to end the frequency cards, and one to end the sequential solution of cases within "LINE CONSTANTS" .

<u>Detail 2</u> : The "88" which is punched in columns 67-68 of the three frequency cards of the "LINE CONSTANTS" data is a signal that it is the zero-sequence mode values which are to be internally linked up with "WEIGHTING" . This is the usual case —— just use of the "WEIGHTING" frequency dependence for the zero sequence mode of a line. If "89" had been punched in columns 67-68 , then line-mode values rather than zero-sequence (ground mode) values would have been communicated back to "WEIGHTING" . Recall that this covers all modes (for an "N"-phase continuously-transposed line, the Karrenbauer diagonalization yields one ground mode and N-1 identical line modes).

Detail 3 : On the two miscellaneous data cards for "WEIGHTING" , only the distance field ("DIST" of columns 1-8 of the first of the two) must always be punched nonzero. Here, the line length is 138 miles. Modal capacitance "CAP" of columns 9-16 will not be used even if it is punched.

Detail 4 : Columns 30-42 of the frequency cards are used to request "LINE CONSTANTS" printout, as explained in Section 7.4 . Such punches are optional, and have no effect on the calculation of weighting functions. The correct line constants information will be communicated from "LINE CONSTANTS" to "WEIGHTING" even if no output is requested, as in this example.

As for the line printer output corresponding to the EMTP solution of such a data case, this will begin with the "LINE CONSTANTS" output. See Section 7.4 for a description of this. Once control is transferred back to "WEIGHTING" from "LINE CONSTANTS" , one sees the following:

} end of "LINE CONSTANTS" data

```
BLANK CARD TERMINATING FREQUENCY CARDS.                        !
BLANK CARD TERMINATING LINE-CONSTANTS CASES.                   !
MISC. DATA.      .1380E+03  -.0           -.0                  !
CAPACITANCE.                                                   !   138.
2ND MISC.     -0    -0    -0    -0    -0    -0                 !  .11560068E-01                                             CARD IMAGE FROM UNIT 9.
R AND L AT  .100E-03HZ.  .300E-01  .172E+02                    !  .30000426E-01   .17185322E+02   .10000000E-03   CARD IMAGE FROM UNIT 9.
R AND L AT  .600E+02HZ.  .305E+00  .574E+01                    !  .30523077E+00   .57358853E+01   .60000000E+02   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .305E-01   .885E+01   .100E+00          !  .30479683E-01   .88516471E+01   .10000000E+00   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .308E-01   .857E+01   .178E+00          !  .30845227E-01   .85742829E+01   .17782794E+00   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .315E-01   .830E+01   .316E+00          !  .31501806E-01   .82969254E+01   .31622777E+00   CARD IMAGE FROM UNIT 9.
LINE CONSY. R,L,F.     .327E-01   .802E+01   .562E+00          !  .32667718E-01   .80198635E+01   .56234133E+00   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .347E-01   .774E+01   .100E+01          !  .34737140E-01   .77430874E+01   .10000000E+01   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .384E-01   .747E+01   .178E+01          !  .38408129E-01   .74686903E+01   .17782794E+01   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .449E-01   .719E+01   .316E+01          !  .44915393E-01   .71987932E+01   .31622777E+01   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .564E-01   .692E+01   .562E+01          !  .56439522E-01   .69155936E+01   .56234133E+01   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .788E-01   .664E+01   .100E+02          !  .78824415E-01   .66411838E+01   .10000000E+02   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .113E+00   .637E+01   .178E+02          !  .11283378E+00   .63679658E+01   .17782794E+02   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .176E+00   .610E+01   .316E+02          !  .17635028E+00   .60962117E+01   .31622777E+02   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .288E+00   .583E+01   .562E+02          !  .28828979E+00   .58261796E+01   .56234133E+02   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .485E+00   .556E+01   .100E+03          !  .48478628E+00   .55578091E+01   .10000000E+03   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .828E+00   .529E+01   .178E+03          !  .82847597E+00   .52910702E+01   .17782794E+03   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .142E+01   .503E+01   .316E+03          !  .14221684E+01   .50265781E+01   .31622777E+03   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .243E+01   .477E+01   .562E+03          !  .24332857E+01   .47660170E+01   .56234133E+03   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .414E+01   .452E+01   .100E+04          !  .41391539E+01   .45184690E+01   .10000000E+04   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .699E+01   .428E+01   .178E+04          !  .69858766E+01   .42794893E+01   .17782794E+04   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .117E+02   .405E+01   .316E+04          !  .11665693E+02   .40530199E+01   .31622777E+04   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .192E+02   .384E+01   .562E+04          !  .19222649E+02   .38413167E+01   .56234133E+04   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .312E+02   .365E+01   .100E+05          !  .31173480E+02   .36467268E+01   .10000000E+05   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .496E+02   .347E+01   .178E+05          !  .49632810E+02   .34714557E+01   .17782794E+05   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .774E+02   .332E+01   .316E+05          !  .77427077E+02   .33172284E+01   .31622777E+05   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .118E+03   .318E+01   .562E+05          !  .11819504E+03   .31849799E+01   .56234133E+05   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .177E+03   .307E+01   .100E+06          !  .17650795E+03   .30745980E+01   .10000000E+06   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .258E+03   .299E+01   .178E+06          !  .25808683E+03   .29865433E+01   .17782794E+06   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .370E+03   .292E+01   .316E+06          !  .37028267E+03   .29207116E+01   .31622777E+06   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .522E+03   .286E+01   .562E+06          !  .52246561E+03   .28633529E+01   .56234133E+06   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .728E+03   .282E+01   .100E+07          !  .72750564E+03   .28177272E+01   .10000000E+07   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .100E+04   .278E+01   .178E+07          !  .10024201E+04   .27840415E+01   .17782794E+07   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .137E+04   .276E+01   .316E+07          !  .13701085E+04   .27589995E+01   .31622777E+07   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .188E+04   .274E+01   .562E+07          !  .18612225E+04   .27403114E+01   .56234133E+07   CARD IMAGE FROM UNIT 9.
LINE CONST. R,L,F.     .252E+04   .273E+01   .100E+08          !  .25167192E+04   .27263353E+01   .10000000E+08   CARD IMAGE FROM UNIT 9.
BLANK CARD TERMINATING LINE CONSTANTS  R, L, F .               !  .0              .0              .0              CARD IMAGE FROM UNIT 9.
```

Detail 5 : Most of these records look like the familiar interpreted card images of EMTP data input, except for the text "CARD IMAGE FROM UNIT 9." which shows up in columns 54-76 . These provide the communication from "LINE CONSTANTS" to "WEIGHTING" ; they are 80-column card-image records, only they are on unit number "LUNIT9" rather than "LUNIT5" (from which the user-supplied data cards are read). Included are one record bearing just the modal capacitance (this record is sandwiched between the two user-supplied miscellaneous data cards) and all of the modal line-constants records bearing R , L , and f values.

Detail 6 : Beyond the printout shown above (i.e., below the bottom of it), output is identical to that for a self-contained "WEIGHTING" case, as illustrated previously.

How to Plot Weighting Functions $a_1(t)$ and $a_2(t)$

If the user wants, he can produce graphs of the weighting functions $a_1(t)$ and $a_2(t)$. This can be either as part of the same "WEIGHTING" data case, or at some later time (e.g., using the "REPLOT" feature, or using interactive CRT plotting). The general procedure should be familiar to EMTP users, since the "WEIGHTING" code of UTPF overlay number 43 has simply been connected to the EMTP plotting code of UTPF overlay number 31 .

For plotting purposes, the names "A1 " and "A2 " are used for identification of the two aforementioned weighting functions. These weighting function variables are handled as though they were node voltages. Plot cards as an EMTP data class are covered in Section 1.10 , where it is noted that a blank card is used for termination. Provided miscellaneous data parameter "MPLOT" (columns 49-56) is punched as unity, such plot cards are to follow either :

a) the blank card which ends line constants (R, L, f), or

b) the blank card which ends the embedded "LINE CONSTANTS" or "CABLE CONSTANTS" data case.

Recall that any given "WEIGHTING" data case will use one or the other of these two options.

Data fields "AXIS" , "MPLOT" , and "MCAT" of the miscellaneous data cards were skipped over in the original explanation. They are associated with the plotting of weighting functions, as follows:

MPLOT —— Punch with unity, if such plotting is desired. If left blank, the user can totally ignore the present section.

MCAT —— Parameter which indicates a possible desire to save the raw plot data points on disk as a permanent file for later reuse (e.g., using "REPLOT" or interactive CRT plotting).

$$\begin{cases} 0 \Longrightarrow \text{No such saving of data points on disk;} \\ 2 \Longrightarrow \text{the raw plot data points \underline{will} be saved as a permanent file on disk.} \end{cases}$$

This is comparable to the use of variable "ICAT" of conventional EMTP data cases (see the integer miscellaneous data card, Section 1.0h), except that here a value of "1" has no meaning. There is no provision for ignoring plot cards, as with a conventional data case.

AXIS ----- Field related to plot scaling. It can be left blank if all plot scaling is to be user-specified, as per the usual rules for batch-mode plotting (see Section 1.10).

When "AXIS" is punched positive, any subsequently produced plots of A1 and A2 will automatically be scaled as follows:

a) Let AMIN be the minimum of A2. Then the plotting fields "VMIN" and "VMAX" (columns 16-24 of the plot-specification card) can be left blank for the A2 plot; the EMTP will internally set these variables to AMIN and -AXIS*AMIN, respectively.

b) Both A1 and A2 plots will have the time axis span the interval (0, TMAX), where TMAX is the end time of the weighting functions (equal to HMAX travel times, by definition). The user is to punch the desired axis length in columns 8-11 (plot field HMIN), and the EMTP will do the rest.

Such automatic plot scaling can not be used with "REPLOT" usage (see Section 1.0d), or with interactive CRT plotting; it only applies to plots which are part of the same "WEIGHTING" data case. Of course the user can punch AXIS positive in any case; but if plots are not produced at the same time, the automatic scaling feature will be inactive.

Regarding the plot cards, it might be explained that the automatic scaling option of AXIS is provided because the negative peak of A2 may not be known beforehand. For A1, there is no scaling problem, since one generally wants to look at the whole positive pulse. But recall that A2 begins at positive infinity at time zero (theoretically), which effectively disables the EMTP automatic plot scaling capability (if columns 16-24 of the plot card are left blank). The philosophy of using positive AXIS is that the user will want to plot all of the negative A2 pulse, plus a part of the initial decay from plus infinity. For example, if the user punches AXIS equal to 4.0, 1/5 of the ordinate excursion will be negative, and 4/5 will be positive.

It should be mentioned that the use of positive "AXIS" is all-enclusive. That is, all plots of the "WEIGHTING" data case in question will have the time axis automatically determined as described. If user-specified scaling of the same solution is also desired, then either "REPLOT" or interactive CRT plotting must subsequently be resorted to.

Another feature of positive "AXIS" is that most of the plot card fields can be left blank. Only the following information is mandatory:

Column 2 --------- Punch "1" always.
Columns 8-11 ------ Punch the desired time-axis length, in inches.
Columns 25-26 ----- Punch either "A1" or "A2".

Labeling information (columns 49-80) of the plot card continues to be at the discretion, as before; it is usually ignored for production work (users are in a hurry).

Suppose that two or more data cases within "WEIGHTING" are contained within a single EMTP data case (which commences with a "BEGIN NEW DATA CASE" card, recall). Then the user should avoid the following situations, at least for the moment:

a) Avoid punching "MCAT" positive on more than one of the contiguous data cases within "WEIGHTING".

b) Avoid all plotting (by leaving "MPLOT" blank) within any "WEIGHTING" data case which follows one with positive "MCAT".

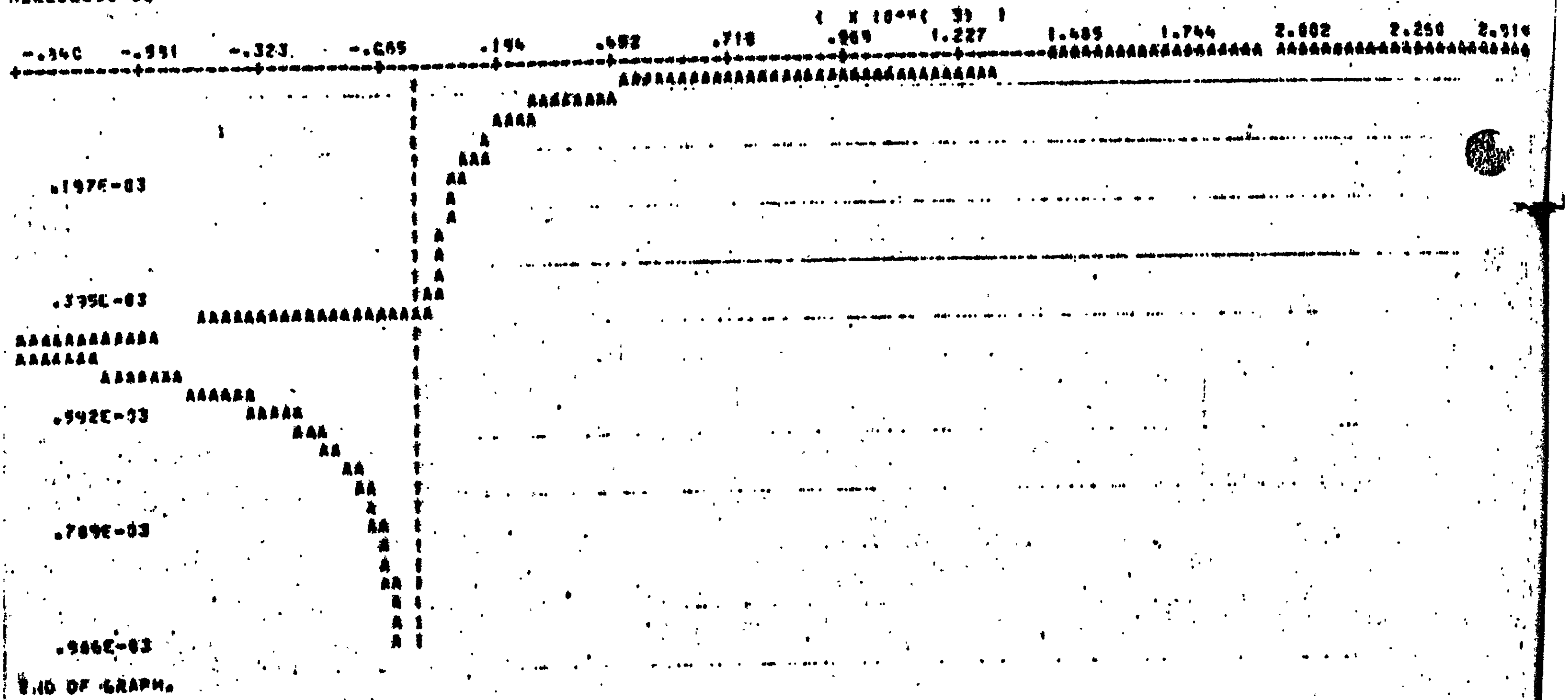
At least on CDC, such situations lead to illegal TAPE4 manipulations, and a subsequent system error stop. Such complications are most simply avoided by never plotting more than once without going through another "BEGIN NEW DATA CASE" card.

As an example of a "WEIGHTING" test case which includes the use of plotting, consider the following data listing:

```
BEGIN NEW DATA CASE
C     UTPF TEST CASE NO. 41
C     TEST OF WEIGHTING-FUNCTION SUPPORTING PROGRAM, WHICH CALCULATES
C     WEIGHTING FUNCTIONS  A1(T)  AND  A2(T)  FOR THE ZERO-SEQUENCE OF
C     DISTRIBUTED-PARAMETER LINES HAVING FREQUENCY-DEPENDENT LINE CONSTANTS
C     THIS DATA CASE IS FOR THE ZERO-SEQUENCE OF AN OVERHEAD LINE HAVING
C     LENGTH EQUAL TO  34.5  MILES.   RESISTANCE AND INDUCTANCE AS A
C     FUNCTION OF FREQUENCY ARE SUPPLIED AS PART OF THE DATA.
WEIGHTING
   34.5  .01210                                                      3.0
                                                                      2
   3.0976000E-02   8.8548000E+00   1.0000000E-01
   3.1627000E-02   8.4387000E+00   2.3713700E-01
                 : Etc. :
   1.6301000E+03   2.7857300E+00   4.2169700E+06
   2.1684000E+03   2.7693500E+00   7.4989400E+06
   2.5202000E+03   2.7629000E+00   1.0000000E+07
              ~ Blank card ending R, L, f
    PRINTER PLOT
  1       5.0          A2
  1       8.0          A1
                  ~ Blank card ending plot cards
          ~ Blank card ending "WEIGHTING" data cases
BEGIN NEW DATA CASE } Nonexistent EMTP data case stops execution
```

This data case is identical to the first "WEIGHTING" illustration, except that plotting has been added. Printed output is likewise identical, through the listing of the "A2" cards which may be punched. Then, rather than showing the "BLANK CARD TERMINATING ALL 'WEIGHTING' CASES.", the following will be seen:

```
                    : Etc. a2(t) :
958.3439    -43.76  962.3305    -43.41  966.3230    -43.01  970.3096    -42.60
974.2991    -42.23  978.2147    -41.82  982.2783    -41.33  986.2678    -40.97
              ---- SUCCESSFUL "STACK" EDITING.  LAST    0  ENTRIES DELETED.   ADDED ENTRY **SM36   02/14/78  12.49.5
              ---- SUCCESSFUL CATALOG OF UNIT-4 PLOT DATA POINTS.   PERMANENT FILE NAME = "PAKLOTFILE021478124955"

REQUEST FOR LINE PRINTER PLOT.                 1  PRINTER PLOT
*** PLOT CARD.      .197E+00    .0        .186E+00  1 1     5.0          A2

 02/14/78  12.49.55       1
 PLOT TYPE    4
 NODE NAMES       A2
```



This shows just the first line printer plot. Such output will continue through the last such plot (this data case had two), after which the expected termination will be recorded:

```
BLANK CARD TERMINATING PLOT SPEC. CARDS.          |
BLANK CARD TERMINATING ALL  "WEIGHTING"  CASES.   |

ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP), CDC TRANSLATION PRODUCED BY THE BONNEVILLE POWER ADMINISTRATION, PORTLAND,
OREGON.   DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) =  02/14/79  12.59.16   ANY PLOTS BEAR THE SAME FIGURES.
IF IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE 544-PAGE EMTP USER'S MANUAL DATED NOVEMBER, 1977.
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF   /LABEL/   EQUALS   6873  INTEGER WORDS.
   40    60   200    10   400    10   400   250     5    30    50    50     5   400    50     4     2     5     1    20   100   100
--------------------------------------------------+---------------------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA | INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER.
                                                  0         1         2         3         4         5         6         7         8
                                                  0         0         0         0         0         0         0         0         0
--------------------------------------------------+---------------------------------------------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.              |BEGIN NEW DATA CASE
BLANK TERMINATION-OF-RUN CARD.                    |
```

7.4 "LINE CONSTANTS" Routine

By means of the special request word "LINE CONSTANTS" , an EMTP user gains access to the supporting routine which bears this same name, as per the explanation of Section 7. . The principal function of this code is to calculate the resistance, inductance, and capacitance matrices which correspond to an arbitrary configuration of overhead conductors.

Prior to July of 1976, the code in question existed as a self-contained, separate program which went by the name of "BPA Line Constants Program". It was originally written by Dr. Hermann W. Dommel, who is now Professor of Electrical Engineering at the University of British Columbia in Vancouver. Details of the incorporation of this routine into the EMTP are covered in the 11-page EMTP memo which is dated June 28, 1976.

So as to leave the original (master) copy of the User's Manual of the BPA Line Constants Program intact, the following 70 or so pages began with a copy. Rather than use a BPA copy, I have availed myself of a B.C. Hydro copy, which was given to me last summer at our July 19, 1976 EMTP reunion by Dr. Brian Dixon of that organization. It would appear that B.C. Hydro has done some editorial enhancement, which included the re-typing of a substantial portion of the text Differences in typewriter font will indicate to the careful observer those passages which have been typed at B.C. Hydro. Hermann's originals are characterized by the same font as is being used for the present paragraph.

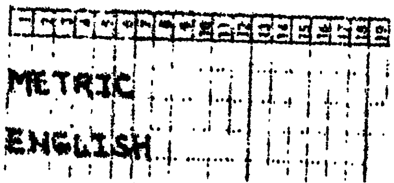
The structure of a data case for "LINE CONSTANTS" is as follows:

1. First comes a "BEGIN NEW DATA CASE" card (actually optional, as per Section 1.0a).
2. Next comes a "LINE CONSTANTS" card, which serves to transfer control to the overlay in question (UTPF overlay number 44).
3. Next come the "conductor cards," which define the line geometry and some of its fundamental electrical properties. There is to be one such card for each physical conductor; a blank card is used to terminate this class of data.
4. Next come the "frequency cards," each of which specifies a new earth resistivity and frequency (or range of frequencies) for which line constants are to be calculated. Such cards are to be terminated by a blank card.
5. Repeat the data of Points 3 and 4 above as often as is desired. Each such group of data represents an independent data case within the "LINE CONSTANTS" overlay. Terminate the last such grouping with a blank card, which serves to transfer control back to the regular EMTP solution-mode, ready to read in a new EMTP data case.
6. If the user wants to shut off the EMTP at this point (rather than execute a following EMTP data case), he should simply add a "BEGIN NEW DATA CASE" card at this point, followed by a blank card. This is as per Section 1.0b .

Metric vs English Units for "LINE CONSTANTS"

Originally, the ntire "LINE CONSTANTS" supporting program used nothing but English units, for it was written in the United States (at BPA) in the decade of the sixties, before any conversion to metric units. Internally, the "LINE CONSTANTS" calculation still is performed in English units. But since 1976, a "METRIC" option for data-card input and line-printer output has been provided (see Ref. 8, Vol. V, June 28, 1976). One can choos either the "METRIC" or the "ENGLISH" option for input/output (I/O), as shall be briefly explained.

Either metric or English units can be ordered for "LINE CONSTANTS" I/O by means of one of the following special-request cards:



METRIC

ENGLISH

Such a card must immediately precede the first conductor card of a data cas within the "LINE CONSTANTS" overlay. That is, it must precede the Point 3 data of "LINE CONSTANTS", as defined near the beginning of Section 7 4 Each data case within the "LINE CONSTANTS" overlay (see Point 3 data description) can have a different choice of units, if so desired by the user

At present, "ENGLISH" units are obtained unless the user explicitely requests otherwise at the beginning of the data case of "LINE CONSTANTS" (as just described).

The units in which input data fields are to be punched are indicated along with the data-format specification. Two rows will be shown ---- one for "ENGLISH" and one for "METRIC". It is the user's responsibility to always supply those units which correspond to his chosen option (which is either "METRIC" or "ENGLISH").

The units for printed output should cause no confusion, for they will be stated in the printed headings which precede such output.

Variabl Dimensioning of "LINE CONSTANTS" Code

As with all other non-solution overlays of the EMTP which require variable-dimensioning, this capability has been provided via a "VDOV" module (SUBROUTINE VDOV44). The available space for "LINE CONSTANTS" arrays is equal to that of /LABEL/ , minus a constant offset (which allows for the excess space required by the compiled code itself). EMTP variable dimensioning allows the user to control the size of /LABEL/ at will, of course (see Section 0.6). Hence "LINE CONSTANTS" is variably-dimensioned, indirectly.

Normally, data cases for "LINE CONSTANTS" will just execute without any difficulty related to dimensioning, and the user need not be at all concerned with program dimensions. Yet there are three distinct ways in which the user might possibly get into trouble, should insufficient central memory be available. For completeness, these shall be listed here:

Bomboff #1

First, suppose that /LABEL/ (as produced by the user's preceding variable-dimensioning operation) is exceedingly small. Suppose further that the user is running the EMTP on a non-Virtual machine, within a central memory partition which is barely adequate for conventional time-step-loop simulations. Then it is possible that the operating system could terminate execution of the run as the EMTP attempts to transfer control from "MAIN00" to "OVER44" (the overlay of the "LINE CONSTANTS" code). Remedy: re-dimension the EMTP in a less-miserly fashion. For CDC in the Spring of 1977, perhaps 4000 or 5000 cells of /LABEL/ is needed as a minimum, in order to escape the fate of Bomboff #1.

Bomboff #2

Having barely escaped Bomboff #1, it is possible for program control to get into "OVER44" only to discover that there is not enough storage available for even two conductors (2 x 2 matrices). For a Virtual machine which will never run into Bomboff #1, it is Bomboff #2 which will be the standard indication of insufficient size for /LABEL/ . A standard EMTP error-termination (KILL-code) message will result, describing the problem. In this case, data input can not even be begun. Remedy: same as for Bomboff #1 above.

Bomboff #3

If the user escapes Bomboffs #1 and #2, then data input for the "LINE CONSTANTS" case begins. But should too many conductor cards for the given dimensioning (size of /LABEL/) be read, then a conventional EMTP error message will result (e.g., see Section 2.4). The error printout will indicate the conductor limit which has been exceeded. Then in order to know how much /LABEL/ must be expanded, the user is advised to consult the following constraint between the maximum number of conductors "n" and the total available array space "T" :

$$T = \frac{11\,n^2}{8} + \frac{91\,n}{4} + 9$$

n	T
3	90
4	135
12	480
18	864
30	1929
40	3119
50	4584

For example, suppose that the error-stop printout indicates that the current program limit is 12 conductors If the data case in question actually has 23 , the user might decide to redimension for a limit of 30 . To do this, /LABEL/ will have to be expanded by at least 1929 - 480 = 1449 floating-point words. The storage is predominately REAL .

Format for Conductor Cards (Point 3 "LINE CONSTANTS" data)

For each physical conductor which belongs to the overhead transmission line, one card is to be punched according to the following format:

IPHASE	SKIN	RESIS	IXTYPE	REACT	DIAM	HORIZ	VTOWER	VMID	SEPAR	ALPHA	NAME	NBUND
I3	F5.4	F8.5	I2	F8.5	F8.5	F8.3	F8.3	F8.3	F8.5	F6.2	A6	I2
ENGLISH		Ω / KM		See Exception 2 below	cm.	meters	meters	meters	CM			
METRIC		Ω /mile			inch	feet	feet	feet	inch			

IPHASE —— The phase number (an integer) to which this conductor
(1-3) belongs. Punch as zero for a ground wire (ground is phase number zero, by definition). If more than one conductor is punched with the same phase number, this means that those conductors are to be bundled (electrically connected in parallel). Use numbers 1 , 2 , etc. without any missing (unused) entries, when numbering the phases.

SKIN ——— Field which is usually punched with the ratio T/D ,
(4-8) where:

- T = thickness of tubular conductor;
- D = outside diameter of tubular conductor.

For a solid conductor, use 0.5 , note.
See Exception 1 below, for an infrequently-used alternative.

RESIS ——— Dc resistance of the conductor, in units of:
(9-16)

- ohm / kilometer ——— if "METRIC"
- ohm / mile ———— if "ENGLISH"

See Exception 1 below, for an infrequently-used alternative .

IXTYPE —— Usually punched with a "4" .
(17-18) See Exception 2 below, for several infrequently-used alternatives.

REACT —— Usually left blank.
(19-26) See Exception 2 below, for several infrequently-used alternatives.

DIAM —— Outside diameter of tubular conductor, in units of:
(27-34)

- centimeters —— if "METRIC"
- inches ——— if "ENGLISH"

HORIZ (35-42) ------ Horizontal separation of the center of the conductor from some reference line, in units of:

meters ------ if "METRIC"
feet ------- if "ENGLISH"

Location of the reference line is arbitrary; distances to the right of it are positive, while those to the left are negative.

VTOWER (43-50) ------ Vertical height of the conductor above the ground, at the tower, in units of:

meters ------ if "METRIC"
feet ------- if "ENGLISH"

See Exception 3 below, for an alternative.

VMID (51-58) ------ Vertical height of the conductor above the ground, at mid-span (midway between two towers), in units of:

meters ------ if "METRIC"
feet ------- if "ENGLISH"

See Exception 3 below, for an alternative.

SEPAR ALPHA (59-72) ----- Leave blank, unless the automatic bundling option is desired, as explained in Exception 4 below.

NAME (73-78) ------ Leave blank, unless the change-case option is to be used, as explained in Exception 5 below.

NBUND (79-80) ------ Leave blank, unless the automatic bundling option is desired, as explained in Exception 4 below.

The just-delineated rules apply to the most common, basic "LINE CONSTANTS" usage; they are the most frequently-used alternative. Yet other options are available, as shall now be explained.

Exception 1 : Bypass skin effect calculation

If the skin-effect correction (or calculation) is to be bypassed (omitted), then enter 0.0 in the field "SKIN" of columns 4-8 . Also for such a case, field "RESIS" of columns 9-16 is to be punched with the conductor ac (not dc) resistance. Recall that ac resistance is equal to dc resistance plus a skin-effect contribution which depends on frequency, among other things.

Exception 2 : Alternative self-inductance calculation

Rather than have the program calculate self-inductance based on the tubular conductor geometry, four other alternatives are available to the user. All involve the reading of one additional floating-point number, from field "REACT" of columns 19-26 . Internal inductance is not corrected for the skin effect in any of these four alternatives. Type code "IXTYPE" of columns 17-18 can take on four alternate values to the usual "4"-punch, as follows:

IXTYPE	REACT (19-26)
0	Reactance for unit spacing, assumed to be valid for whatever frequencies may be encountered on frequency cards which follow. The unit spacing is : one meter ------ if "METRIC" one foot ------ if "ENGLISH" The reactance "REACT" is in units of: ohm/kilometer ---- if "METRIC" ohm / mile ------ if "ENGLISH"
1	Just like immediately above, only this reactance only applies at 60 Hertz. If frequencies different than this will be encountered on frequency cards which follow, the reactance will be changed proportionately.
2	GMR (geometric mean radius) of the conductor, in units of: centimeters ----- if "METRIC" inches -------- if "ENGLISH"
3	Dimensionless ratio GMR r , where "r" is the conductor outer radius. For solid conductors, this ratio is equal to .7788 .

Exception 3 : Usage of conductor vertical heights

Before considering alternatives, first consider how "VTOWER" and "VMID", the conductor vertical heights at the tower and at mid-span, enter the calculation. It may be recalled that Carson's formula requires conductors to be parallel to the (assumed) flat earth. Of course conductors always sag, so an average height must be used as an approximation. The program uses

$$VMID + \left[\frac{VTOWER - VMID}{3}\right] = 2/3 \cdot VMID + 1/3 \cdot VTOWER$$

if both fields are punched non-zero.

If one of the two data fields "VTOWER" and "VMID" is left blank, the program assumes a value equal to that which was read from the other field. This is the way the user can input the average height himself ---- by just punching one of the tw fields.

Exception 4 : Automatic bundling option

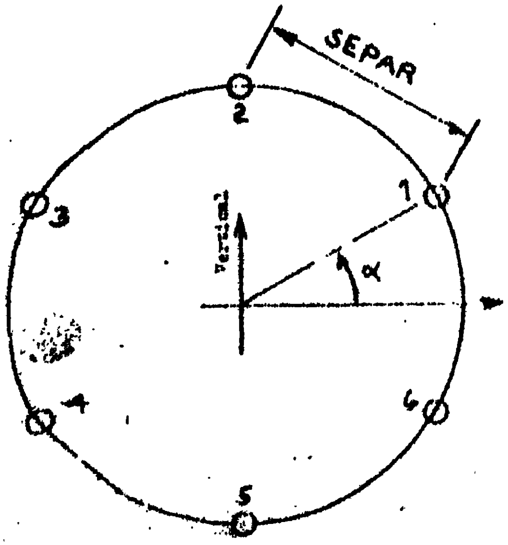
Rather than specify each conductor of a bundle individually, there is an automatic bundling option which allows a single conductor card to suffice for specification of the entire bundle. This can be used for a "regular" bundle, where by definition all component conductors are identical, and such conductors are also assumed to be uniformly spaced around the circumference of a circle.

Automatic bundling uses the data fields "SEPAR", "ALPHA", and "NBUND", which are otherwise left blank. The "conductor" card then becomes a "bundle" card, as per the following specification:

SEPAR (59-66) ----- Separation between adjacent conductors in the bundle, in units of:
- centimeters ----- if "METRIC"
- inches --------- if "ENGLISH"

ALPHA (67-72) ----- Angular position of the first conductor (or any conductor) of the bundle, in units of degrees. Positive angles are measured counter-clockwise, as shown in the sketch.

NBUND (73-80) ----- Number of conductors which make up the bundle.



Sample sketch of a bundle of NBUND = 6 conductors, with angle "ALPHA" equal to 30 degrees.

Exception 5 : Naming of conductors for change-case identification.

Data field "NAME" of columns 73-78 is normally left blank, unless a following data case within "LINE CONSTANTS" is to make use of the change-case feature. See later explanation For such change-case usage, conductors must be identified. A 6-character alphanumeric name is used for this purpose, punched in columns 73-78 using A6 format. Only those conductors which will later be referenced must be given distinct 6-character names.

Format for Frequency Cards (Point 4 "LINE CONSTANTS" data)

For each discrete frequency or logrithmically-spaced grouping of frequencies for which line constants are to be calculated, there is to be a frequency card of the following format:

Earth resistivity RHO	frequency FREQ	Carson accuracy FCAR	Print [C] ICPR	Print [Z] IZPR		distance DIST	Print Pi IPI[illegible]		IDEC	[illegible]	IPNT
F8.4	F10.2	F10.6	6I1	6I1		F8.3	4I1		I3	I2	I3

RHO (1-8) ---- Resistivity of the homogeneous Carson earth, in units of ohm-meters . These units apply both to "METRIC" and "ENGLISH" data cases.

FREQ (9-18) ---- Frequency f of the line constants calculation, in units of Hertz . For logarithmic looping over two or more frequencies, this is the beginning frequency f_1 (see "IDEC" of columns 60-62).

FCAR (19-28) ---- Punch a "1" in column 28 , in order to get full precision in the evaluation of Carson's formula. This is the standard production usage. Other options are described elsewhere.

ICPR (30-35) ---- Printout control parameters for the capacitance matrices $[C]$, or the susceptance matrices $\omega[C]$, or the inverses of these. Variable "ICAP" of column 44 controls the inverse option, note. Six possible independent printed outputs can be requested by means of "1" punches in the appropriate columns:

Column #	Resulting printout
30	Inverse of $[C]$ or $\omega[C]$
31	Inverse of $[C_E]$ or $\omega[C_E]$
32	Inverse of $[C_S]$ or $\omega[C_S]$
33	$[C]$ or $\omega[C]$
34	$[C_E]$ or $\omega[C_E]$
35	$[C_S]$ or $\omega[C_S]$

Here subscripts (or lack of them) have meaning:

none ---- for the unreduced system. Each physical conductor has a row and column in the matrix, as does each ground wire.

"E" ---- for the equivalent phase conductors (after elimination of ground wires and the bundling of conductors).

"S" ---- for the symmetrical components of the equivalent phase conductors.

IZPR (37-42) ---- Printout control parameters for the series impedance matrices $[Z] = [R] + j\omega[L]$ or their inverses. Six possible independent printed outputs can be requested by means of "1" punches in the appropriate columns:

Col. #	37	38	39	40	41	42
Output	Z	Z_E	Z_S	Z^{-1}	Z_E^{-1}	Z_S^{-1}

ICAP (44) ------ Control over whether it is $[C]$ or $\omega[C]$ that will be outputted by any "ICPR" requests of columns 30-35 :

$$\begin{cases} 1 \Rightarrow [C] & \text{or its inverse} \\ 0 \Rightarrow \omega[C] & \text{or its inverse} \end{cases}$$

DIST (45-52) ---- Length of the transmission line under consideration, in units of

$$\begin{cases} \text{kilometers ---- if "METRIC"} \\ \text{miles ------- if "ENGLISH"} \end{cases}$$

This field can usually be left blank. It need be punched only for the following situations:

1) For use with "SEMLYEN SETUP" ; see Section 7.5
2) For the development of a Pi-equivalent using long-line formulas. See "IPIPR" below.

IPIPR (54-57) ---- Printout control for the equivalent-Pi matrices of a long transmission line. Four possible independent printed outputs can be requested by means of "1" punches in the appropriate columns:

Col. #	54	55	56	57
output	Y	Y_S	Z	Z_S

See further discussion elsewhere.

ISEG (58) ----- A flag indicating whether ground wires (if any) are to be treated as being continuous, or instead segmented:

$$\begin{cases} 0 \Rightarrow \text{continuous ground wires (the normal case);} \\ 1 \Rightarrow \text{segmented ground wires (cut at relatively short intervals).} \end{cases}$$

See further discussion elsewhere

MUTUAL (59) ------ A flag which is used to indicate the presence of a communication circuit parallel to the power circuit:

- 0 ⇒ there is no such communication circuit (which is the normal case);
- 1 ⇒ yes, produce special output for a nearby communication circuit. See further discussion elsewhere.

IDEC (60-62) ------ Leave blank for the normal single-frequency line constants calculation.

For the case of internal looping over logarithmically-spaced frequencies, "IDEC" is the number of decades which are to be spanned.

IPNT (63-65) ------ Leave blank for the normal single-frequency line constants calculation.

For the case of internal looping over logarithmically-spaced frequencies, "IPNT" is the number of points per decade at which line constants are to be calculated.

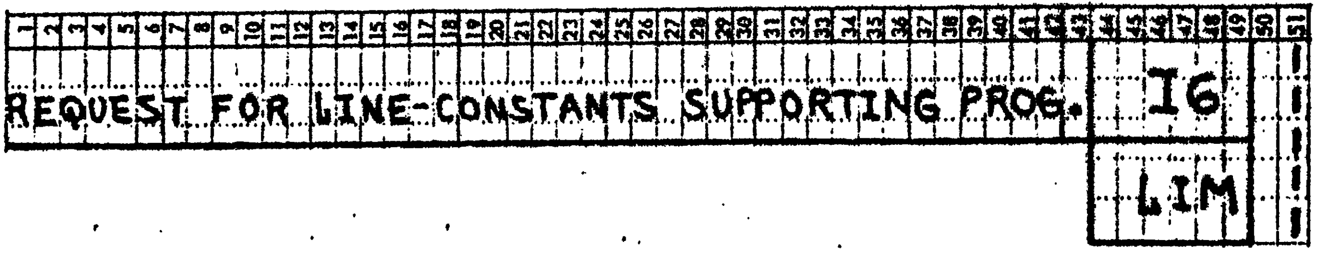
IPUN (66-68) ------ Normally this field is left blank. It is used to request non-printed output of modal quantities, in the case of internal looping over logarithmically-spaced frequencies. Punch :

- "88" ------ For the connection of zero-sequence (ground mode) impedances with "WEIGHTING" . This has meaning only when a "LINE CONSTANTS" data case is imbedded in a "WEIGHTING" data case.
- "89" ------ As just described for "88" , only for the Karrenbauer line mode (rather than the ground mode).

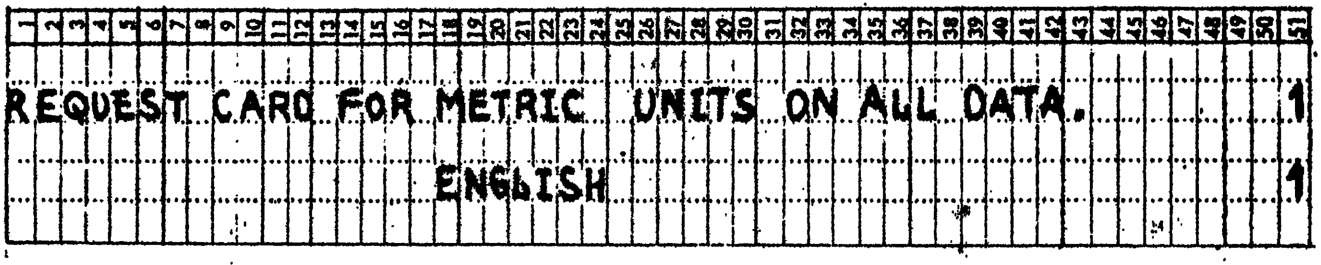
Interpretation of Input Data Cards

As explained in Section 2.1 , input data cards are listed in columns 52-131 of the line printer; a "1" is printed in column 51 as a separator character, and columns 1-50 are used for "interpretation" of the card image. All interpretations related to "LINE CONSTANTS" are explained in the present section.

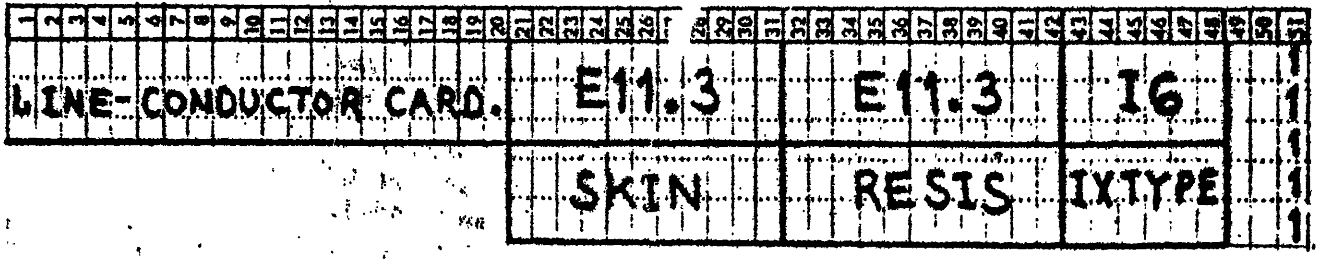
First, there is the special request card which bears the key word "LINE CONSTANTS" (see Section 1.0g) . If we let variable "LIM" stand for the maximum number of line conductors that current EMTP dimensioning will allow, interpretation is as follows:



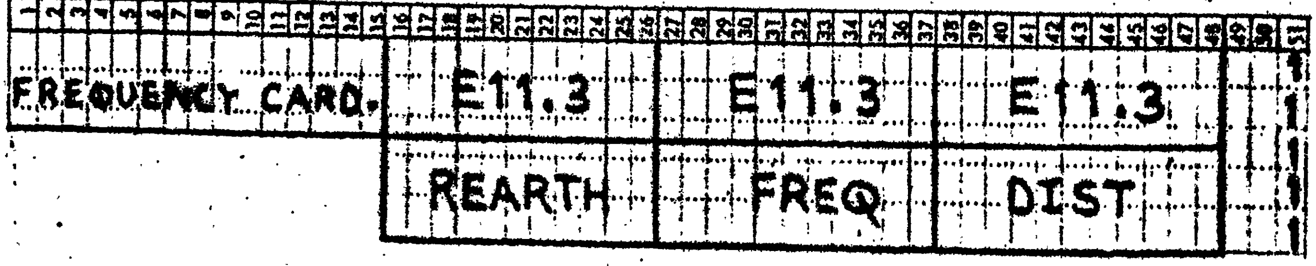
Next comes a possible "METRIC" or "ENGLISH" special request card (which serves to request either metric or English units for input/output data) Interpretations of these two optional cards are as follows:



Next come the line conductor cards, which are interpreted as follows:



Next come frequency cards, which bear the following interpretation:



The beginning of a change case is a special-request card which bears the key word "CHANGE" . This is interpreted as follows:

675

REQUEST CARD FOR CHANGE-CASE OPTION. 1

Blank cards are used to mark the ends of three classes of data within th "LINE CONSTANTS" supporting program:

1) Conductor cards; 2) Frequency cards; and

3) Data cases within "LINE CONSTANTS" .

These are interpreted as follows:

BLANK CARD TERMINATING CONDUCTOR CARDS. 1

BLANK CARD TERMINATING FREQUENCY CARDS. 1

BLANK CARD TERMINATING LINE-CONSTANTS CASES. 1

Sample "LINE CONSTANTS" EMTP Data Case

As a sample EMTP data case which uses "LINE CONSTANTS" , consider a listing of UTPF Test Case #108. Comment cards will be noted in the listing below Note that within this one EMTP data case, there are two "LINE CONSTANTS" data cases. The first uses "ENGLISH" units, while the second uses "METRIC" . Only a single frequency (60 Hz) is involved in each.

```
BEGIN NEW DATA CASE
C     UTPF TEST CASE NO. 108
C     CALCULATE LINE CONSTANTS FOR OVERHEAD LINE USING  "LINE CONSTANTS" .
C     THE LINE IS UNTRANSPOSED, WITH ONE CONDUCTOR PER PHASE.
C     SINGLE 3-PHASE CIRCUIT, WITH 2 GROUND WIRES.
C     THIS IS A COMPANION CASE TO UTPF TEST CASE NO. 107.
C     THE GEOMETRY OF THE OVERHEAD LINE IS THE SAME IN THESE TWO CASES.
C     OF COURSE, HERE WE MUST USE THE HOMOGENEOUS EARTH (1-LAYER).
LINE CONSTANTS
ENGLISH
  1.3871.26715  4          .688   0.0     82.02   41.01   15.75   45.      4
  2.3871.26715  4          .688  45.93    82.02   41.01   15.75   45.      4
  3.3871.26715  4          .688  91.86    82.02   41.01   15.75   45.      4
  0.5   .71498  4          .487   9.84   114.83   57.42
  0.5   .71498  4          .487  82.02   114.83   57.42
                 Blank card endin conductor cards
   200.        60.         1 111111 111111 1  49.71
                 Blank card ending frequency cards
METRIC
  1.3871.16603  4        1.748    0.0     25.0    12.5    40.     45.      4
  2.3871.16603  4        1.748   14.0     25.0    12.5    40.     45.      4
  3.3871.16603  4        1.748   28.0     25.0    12.5    40.     45.      4
  0.5   .4468   4          1.236  3.0     35.     17.5
  0.5   .4468   4          1.236 25.0     35.     17.5
                 Blank card ending conductor cards
   700.        60.         1 111111 111111 1  80.0
                 Blank card ending frequency cards
                 Blank card ending "LINE CONSTANTS" data cases.
BEGIN NEW DATA CASE
```

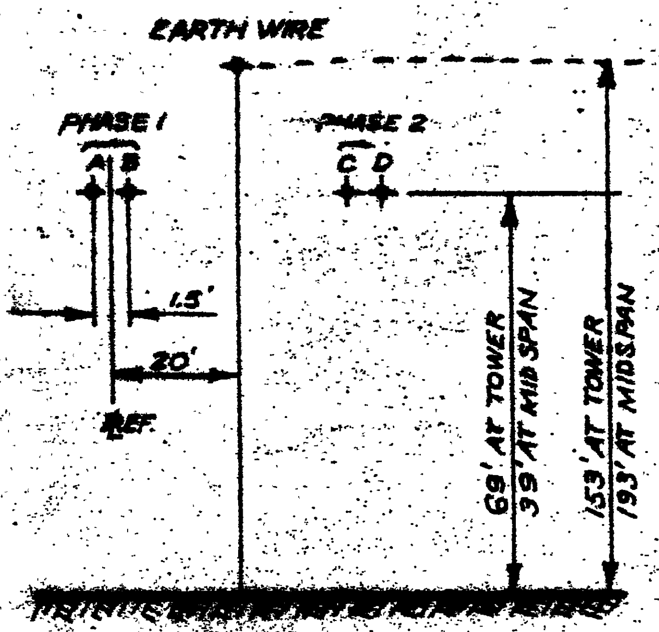
The EMTP line printer output corresponding to the solution of this data case begins as shown on the following page. It will be noted that there is always printout of a sorted line-conductor table, before printout of any of the requested matrices.

```
ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP). CDC TRANSLATION PRODUCED BY THE [illegible]
OREGON.   DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) =   [illegible]
IF IN DOUBT AS TO WHAT THE FOLLOWING PRINTOUT MEANS, CONSULT THE [illegible]
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF   /LABEL/  EQUALS   7154 [illegible]
  50   50  300   20  500   10  500  400   15   30   50   50    5  [illegible]
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA I INPUT DATA CARD IMAGES PRINTED BELOW, [illegible]
                                                  0        1        2        3        4
                                                  0        0        0        0        0
MARKER CARD PRECEDING NEW DATA CASE.              IBEGIN NEW DATA CASE
COMMENT CARD.                                     1C     UTPF TEST CASE NO. 108
COMMENT CARD.                                     1C     CALCULATE LINE CONSTANTS FOR OVERHEAD LINE USING "LINE CONSTANTS".
COMMENT CARD.                                     1C     THE LINE IS UNTRANSPOSED, WITH ONE CONDUCTOR PER PHASE.
COMMENT CARD.                                     1C     SINGLE 3-PHASE CIRCUIT, WITH 2 GROUND WIRES.
COMMENT CARD.                                     1C     THIS IS A COMPANION CASE TO UTPF TEST CASE NO. 107.
COMMENT CARD.                                     1C     THE GEOMETRY OF THE OVERHEAD LINE IS THE SAME IN THESE TWO CASES.
COMMENT CARD.                                     1C     OF COURSE, HERE WE MUST USE THE HOMOGENEOUS EARTH (1-LAYER).
REQUEST FOR LINE-CONSTANTS SUPPORTING PROG.    60 ILINE CONSTANTS
REQUEST CARD FOR ENGLISH UNITS ON ALL DATA.       1ENGLISH
LINE-CONDUCTOR CARD.   .387E+00   .267E+00    4   1  1.3871.26715   4          .688    0.0     82.02   41.01   15.75   45.      4
LINE-CONDUCTOR CARD.   .387E+00   .267E+00    4   1  2.3871.26715   4          .688   45.93    82.02   41.01   15.75   45.      4
LINE-CONDUCTOR CARD.   .387E+00   .267E+00    4   1  3.3871.26715   4          .688   91.86    82.02   41.01   15.75   45.      4
LINE-CONDUCTOR CARD.   .500E+00   .719E+00    4   1  0.5   .71890   4          .487    9.81   114.83   57.42
LINE-CONDUCTOR CARD.   .500E+00   .719E+00    4   1  0.5   .71890   4          .487   82.02   114.83   57.42
BLANK CARD TERMINATING CONDUCTOR CARDS.           1
FREQUENCY CARD.   .200E+03   .600E+02   .497E+02 1 200.        60.            1 111111 111111 1  49.71

LINE-CONDUCTOR TABLE AFTER SORTING AND INITIAL PROCESSING.
TABLE   PHASE    SKIN EFFECT    RESISTANCE   REACTANCE-DATA SPECIFICATION    DIAMETER   HORIZONTAL   AVG HEIGHT   CONDUCTOR
 ROW   NUMBER       R-TYPE     R (OHM/MI)    X-TYPE    X(OHM/MI) OR GMR      (INCHES)    X (FEET)     Y (FEET)      NAME
  1      1          .38710       .26715        4           -.000000            .68800       .656       54.024
  2      2          .38710       .26715        4           -.000000            .68800     46.586       54.024
  3      3          .38710       .26715        4           -.000000            .68800     92.516       54.024
  4      1          .38710       .26715        4           -.000000            .68800      -.656       54.024
  5      1          .38710       .26715        4           -.000000            .68800      -.656       54.024
  6      1          .38710       .26715        4           -.000000            .68800      -.656       55.336
  7      2          .38710       .26715        4           -.000000            .68800       .656       55.336
  8      2          .38710       .26715        4           -.000000            .68800     45.274       54.024
  9      2          .38710       .26715        4           -.000000            .68800     45.274       55.336
 10      3          .38710       .26715        4           -.000000            .68800     46.586       55.336
 11      3          .38710       .26715        4           -.000000            .68800     91.204       54.024
 12      3          .38710       .26715        4           -.000000            .68800     91.204       55.336
 13      0          .50000       .71890        4           -.000000            .48700     92.516       55.336
 14      0          .50000       .71890        4           -.000000            .48700      9.810       76.557
                                                                                          82.020       76.557

FOLLOWING MATRICES ARE FOR EARTH RESISTIVITY=  200.00 OHM-M AND FREQUENCY=      60.00 HZ. CORRECTION FACTOR=  .000001

        INVERTED CAPACITANCE MATRIX (DARAF-MILE) FOR THE SYSTEM OF PHYSICAL CONDUCTORS
                    ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

  1   .91974E+08

  2   .10482E+08   .91974E+08

  3   .48566E+07   .10482E+08   .91974E+08

  4   .49264E+08   .10217E+08   .47592E+07   .91974E+08

  5   .45528E+08   .10326E+08   .48358E+07   .49398E+08   .92242E+08

  6   .49398E+08   .10592E+08   .49281E+07   .45528E+08   .49532E+08   .92242E+08

  7   .10758E+08   .49284E+08   .10217E+08   .10482E+08   .10592E+08   .10868E+08   .91974E+08

      .10868E+08   .45528E 08   .10326E+08   .10592E+08   .107[illegible]08   .10988E+08   .49398E+08   .92242E 08
```

CONDUCTOR CARD

PHASE NUMBER	SKIN EFFECT CORR.	RESISTANCE (Ω/MILE) TOTAL IF NOT CORRECTED FOR SKIN EFFECT	REACTANCE DATA: TYPE	REACTANCE DATA: REACTANCE OR GMR, OR GMR/RADIUS	DIAMETER (INCHES)	HORIZONTAL DISTANCE FROM REFERENCE LINE (FT)	HEIGHT (FEET): AT TOWER OR AVERAGE	HEIGHT (FEET): AT MIDSPAN OR AVERAGE	FOR BUNDLE CONDUCTORS: SEPARATION OF ADJACENT CONDUCTORS (INCHES)	FOR BUNDLE CONDUCTORS: ANGULAR LOCATION OF FIRST CONDUCTOR (DEGREES)	CONDUCTOR NAME (IF ANY)	[illegible]
I2	F5.4	F5.5	I2	F25	F8.5	F8.3	F23	F23	F25	F4.2	A4	I2
1	.3871	.0398	2	.7092	1.802	-.75	69.	39.			A PH-1	
1	.3871	.0398	2	.7092	1.802	.75	69.	39.			B PH-1	
2	.3871	.0398	2	.7092	1.802	40.	69.		18.	0.		2
0	.5	3.11	1	.484	.495	20.	133.	103.			GROUND	

EXAMPLE (DC Line):

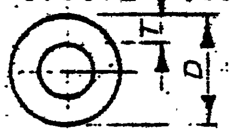


Conductors A,B,C,D: R = 0.0398 Ω/mile

GMR = 0.7092"

DIAMETER = 1.802"

$\frac{T}{D}$ = 0.3871 (for skin effect correction)



Earth Wire: R = 3.1 Ω/mile

Reactance for 1' spacing at 60 Hz = 0.484 Ω/mile (changed proportionately for other frequencies).

DIAMETER = 0.495"

$\frac{T}{D}$ = 0.5 (for skin effect correction)

Instructions for Punching Conductor Cards

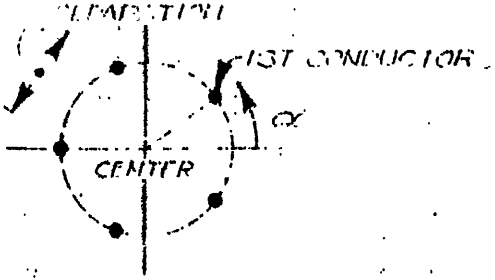
TIME-SAVING FEATURES

1) Identical conductors: If any of the first 6 variables on the card (phase number, skin effect, resistance, X-type, reactance or diameter) are left blank (punching a zero is not blank!), the variable value will be assumed to be the same as it was on the previous card. However, the horizontal distance and at least one height position must be punched for each conductor.

2) Bundle conductors: A bundle of K conductors can be identified in two ways. One can either punch a card for each of the K conductors or punch only one card for the entire bundle. Both ways are shown in the example on the preceding page. If the entire bundle is specified on one card, then

   (a) specify the location of the centre of the bundle in the fields for horizontal distance and heights,

   (b) specify SEPARATION of adjacent conductors of a bundle (inches). Bundled conductors are assumed to be arranged on a circle around the center at equal distances (or equal angles).



   (c) specify ANGULAR LOCATION α of first conductor. Positive angles are measured counter-clockwise from the center (see sketch).

   (d) specify NUMBER OF CONDUCTORS in the bundle (this variable plus separation determines the diameter of the bundle).

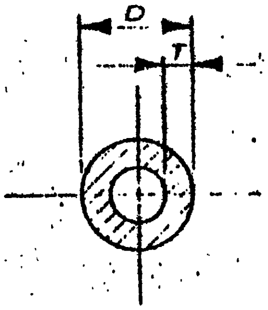
EXPLANATION OF PARAMETERS

Phase Number: A phase on a transmission line may consist of more than 1 conductor (bundle conductors or parallel connected circuits). The PHASE NUMBER defines to which phase the conductor belongs. Number the phases 1 to N consecutively and use "0" for ground wires. Conductors with phase number "0" will be eliminated as ground wires and conductors with identical phase numbers will be bundled into one equivalent phase conductor, no matter whether the bundle is specified on one conductor card or by individual conductor cards. If PHASE-NUMBER < 0 then the conductor is regarded as non-existent (helpful in change cases when removing conductors).

Skin Effect Correction:

= 0, if no skin effect correction is desired.

= $\frac{T}{D}$ if resistance and internal inductance (the latter only when XTYPE=4) are to be corrected for skin effect with the formula for tubular conductors, whereby



$\frac{T}{D} = \frac{\text{thickness of tube}}{\text{diameter of tubular conductor}}$

Note that $\frac{T}{D} = 0.5$ for solid conductors.

Resistance: Conductor resistance in Ω/mile for direct current (or for specific frequency if there is no skin effect correction).

Reactance Data: There are five options for input of reactance data, depending on the value of X-TYPE.

XTYPE = 0: Reactance for 1'-spacing.* This is regarded as the correct value for whatever frequencies may be defined on the following frequency cards.

= 1: Reactance for 1' spacing at 60 Hz.* If frequencies other than 60 Hz appear on the frequency cards, the reactance will be changed proportionately.

= 2: GMR (geometric mean radius) of conductor in inches.

= 3: ratio GMR/radius (is 0.7788 for solid conductors).

Internal inductance is not corrected for skin effect

= 4: Reactance computed from geometry of tubular conductor (defined by $\frac{T}{D}$.) Value for reactance data is ignored. This is indicated in output. Internal inductance is corrected for skin effect.

---

* Relationship between reactance for 1'-spacing and GMR (geometric mean radius):

$$X_{1'\text{spacing}}\ (\Omega/\text{mile}) = \frac{\frac{f[\text{Hz}]}{100} \times 0.20223653}{2\omega \times 1.609344 \times 10^{-4}} \ln \frac{12}{\text{GMR}[\text{inches}]}$$

Diameter: Conductor diameter in inches.

Horizontal Distance: Horizontal distance of middle of conductor from the reference mark. The reference mark may be located anywhere (often, the middle of the tower structure is us d as reference).

Height at Tower:
Height at Midspan: The average height of the conductor is taken as HEIGHT AT MIDSPAN + 1/3 × (HEIGHT AT TOWER-HEIGHT AT MIDSPAN). If the average height is used as input, punch the same value in both fields or leave one blank (if either one is left blank (not '0') then its value will be assumed to be identical to the other one).

Conductor Name: Can be left blank if no change cases are run. Serves to identify conductors for change cases.

FREQUENCY CARD

	EARTH RESISTIVITY IN Ω-m²/m (Ω-m)	FREQUENCY (MUST BE ≠0) IN HZ	EARTH RETURN CORRECTION (ENTER "1" IN COLUMN 28 FOR HIGHEST ACCURACY)	ENTER "1" TO GET INDICATED MATRICES FOR CAPAC. OR SUSCEPT. PER MILE (*)	ENTER "1" TO GET INDICATED MATRICES FOR IMPEDANCE PER MILE (*)	CAPACITANCE OPTION	LINE LENGTH IN MILES (USE ONLY TO DEVELOP EQUIVAL. CIRCUIT WITH LONG LINE FORMULA)	ENTER "1" TO GET INDICATED MATRICES FOR EQ. π CIRCUIT (*) ADMITTANCE ADMITTANCE S IMPEDANCE IMPEDANCE S	GROUND WIRE SEGMENTATION	PARAMETERS FOR SPECIAL OUTPUTS
FORMAT	F8.2	F10.2	F10.6	[illegible]	[illegible]	[illegible]	F8.3	[illegible]	[illegible]	
EXAMPLE	100.	60.	1	1	11		1	1		

(*) MEANING OF SUBSCRIPT: none = for all conductors
E = for the equivalent phase conductors (after bundling and elimination of earth wires)
S = for the symmetrical components of the equivalent phase conductors

EXAMPLE:

For an earth resistivity of 100 Ω-m²/m and for $f = 60$ Hz the following matrices will be computed: Capacitance and impedance matrices per mile for the equivalent phase conductors and the admittance matrices for symmetrical components of the equivalent circuit for $l = 200$ miles. Highest accuracy in earth return correction

EXPLANATION OF SOME PARAMETERS:

Earth Return Correction: Controls the number of correction terms in Carson's earth-return formula for the impedances (see also p. 45).

"1" in col. 28: Normally used (gives highest accuracy). Use always, unless certain effects are desired.

"0": No correction term added (amounts to zero earth resistivity).

≥ 1: As many correction terms are added as specified by this value (rounded to nearest integer), but not more than 31 if $a \leq 5$ (see p. 46). For $a > 5$, eq. (35) of p. 46 is used.

<1: As many correction terms are added as are necessary to get two successive corrections terms (in cgs units/cm as defined by Carson) smaller in magnitude than this value if $a \leq 5$. For $a > 5$ eq. (35) is used. Note that the magnitude of the correction terms is <0.4 cgs-units/cm for resistance and usually of the order 1.0 for reactance. Therefore, "1" in col. 28 yields the highest accuracy of 10^{-6} and does not cost noticeabl computer time.

blank: Automatically set to 10^{-6} (is equivalent to "1" in col. 28).

Enter "1" To Get. . .: Note that all output options (columns 30-35, 37-42 and 54-57) are independent of one another. Meaning of these matrices is explained on p.13.

Capacitance Option:

0 or blank = all matrices indicated in col. 30-35 will be susceptance matrices (ωC) or their inverses.

1 = all matrices indicated in col. 30-35 will be capacitance matrices or their inverses.

Columns 54 to 57: The admittance and/or impedance matrices will be the shunt admittance (impedance) matrix and the transfer admittance (impedance) matrix of the equivalent multiphase π-circuit for the untransposed line.

Ground Wire Segmentation:

0 or blank = Normal

1 = Segmented ground wires (interrupted at certain intervals). Since segmented ground wires cannot carry any current if wave length >> length of segmentation interval, it is felt that the segmentation is best handled by ignoring the ground wires in computing the series impedance matrices and by taking them into account in computing the shunt capacitances matrices. This technique is activated by "1" in col. 58. Note that this approach may not be valid at higher frequencies.

Parameters for Special Outputs:

See P. 17 for getting mutual impedance between a power circuit and a communication line.

See P. 18 for getting the frequncy-dependence of zero and positive sequence parameters.

SYMMETRICAL COMPONENTS:

Symmetrical component matrices are normally * computed with the assumption that the circuits are three-phase circuits. The well-known transformations are used (a,b,c = phase quantities):

$$\begin{bmatrix} V_{zero} \\ V_{positive} \\ V_{negative} \end{bmatrix} = k_1 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \text{identical for currents}$$

$$\text{and} \quad \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = k_2 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{zero} \\ V_{positive} \\ V_{negative} \end{bmatrix}$$

with $a = e^{j120°}$ and $k_1 \cdot k_2 = 1/3$ (usually k_1 $1/3$, $k_2 = 1$; for normalized components : $k_1 = 1/\sqrt{3}$, $k_2 = 1/\sqrt{3}$).

. . . /9

---

*Exception: 2-phase circuit (see next page)

Example: If the number of phases (= equivalent phase conductors) is 6, then it is assumed that no. 1, 2, 3 form the first three-phase circuit and no. 4, 5, 6 form the second three-phase circuit. The symmetrical components will be those of each circuit and the coupling between them.* If the number of phases were 7, then the seventh equivalent phase conductor would be ignored as non-existent in computing symmetrical components.

For two-phase circuits with two phases (example: DC intertie) the symmetrical components are based on the following transformation:

$$V_{zero} = k_1(V_a+V_b)$$

$$V_{positive} = k_1(V_a+V_b)$$, identical for currents,

and

$$V_a=k_2(V_{zero}+V_{positive})$$

$$V_b=k_2(V_{zero}-V_{positive})$$

with

$k_1k_2=\frac{1}{2}$ (usually: $k_1 = \frac{1}{2}$, $k_2 = 1$; for normalized components:

$$k_1 = \frac{1}{\sqrt{2}},\ k_2 = \frac{1}{\sqrt{2}})\ .$$

---

* The results are valid for the given tower configuration with the assumption that the line is untransposed. For transposed single circuits simply ignore the coupling between sequence quantities (see p. 29). There is no simple answer for transposed double circuit lines, except that coupling always exists in the zero sequence with the correct values shown in the 6 x 6 matrix. The transposition scheme on p. 47 has no positive sequence coupling; therefore, simply take the positive sequence values of each circuit and ignore the coupling in the 6 x 6 matrix (or, if both circuits are identical, the impedance of the circuits in parallel is simply one half of the impedance of one circuit). On the other hand, the transposition scheme on p. 49 has positive sequence coupling and the impedance of the circuits in parallel is no longer simply one half of the impedance of one circuit. More details on these and other transposition schemes can be found in a note "Preliminary Conclusions on Influence of Transposition Schemes on Positive Sequence Values" dated 10/20/72. Since this note gives only preliminary results, more work may be required.

. . . ./10

if the user punches a "1" in col. 35 as well as in col. 39, then the computer will also print surge impedance, attenuation, wave velocity and wave length for zero and positive sequence (for the first three-phase circuit only if there are more than one three-phase circuit), as well as series impedance and shunt admittance per mile.

TRANSPOSED VERSUS UNTRANSPOSED LINE

The line constants are computed for the true tower configuration, which is always untransposed. When the line is transposed, the series impedance matrix per-unit length is traditionally obtained form the arithmetic average of the impedance matrices of the individual transposition sections (analogous for shunt admittance matrix). This "theoretical transposition" is an approximation; the exact results would be obtained from a series connection of the untransposed equivalent multi-π's of the individual transposition sections (however, the symmetrical component impedances would have some coupling in the latter case).

For practical purposes the assumption of theoretcial transposition is imperative if the sequence impedances should be decoupled. It can be shown that the sequence impedances obtained from the program for the untransposed line are equal to those of theoretical transposition if the coupling terms are simply ignored. A more detailed 10-page note on this problem is available from Dr. H. W. Dommel.

CHANGE CASE

Normally, each DATA DECK defines a new case. However, the CHANGE option permits changes in the conductor data of a preceding DATA DECK. The DATA DECK of the CHANGE option is set up as follows:

1. One alphanumeric card with the word "CHANGE" in the first 6 columns.

2. Conductor cards in any order, terminated by a BLANK card. These cards are interpreted as additions, deletions or changes in the conductor list of the preceding DATA DECK (of the same run), with the following rules:

   a. If the conductor name (col. 73-78) can be found in the conductor list (established from preceding DATA DECK with modifications already made), then the parameters on this card replace the old values in the list ("changes"). Changes only apply to the first 6 fields on the card. The conductor name and location cannot be changed. To change the location of a conductor, the conductor must be deleted and a new conductor entered. Of the first 6 fields, only those which are punched will be changed. Fields left blank will keep the variables unchanged. A conductor can be removed from the list by reading in a new conductor card with identical conductor name and a phase number <0 ("deletions").

   b. If the conductor name cannot be found in the conductor list, then the new conductor is added to the list ("additions"). In this case, all data must be punched.

3. Any number of frequency cards, terminated by a BLANK card.

Form of Output for LINE CONSTANTS

The output should be more or less self-explanatory. Additional remarks have been written into the attached sample output sheets.

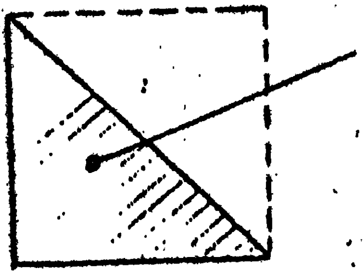
(a) Listing of Conductor Cards

The information contained on the conductor cards of the input data deck is printed for the record in its original form, with the exception of height at tower and midspan. Instead, the averaged height is listed as Y-coordinate. The order of the conductor cards in the input data deck is arbitrary; the order in the listing will always be:

Conductors first encountered with phase numbers 1, 2, 3, ..., followed by conductors with identical phase numbers (= 2nd, 3rd, 4th, ... conductors in 2-, 3-, 4-conductor-bundles), followed by ground wires (phase number = 0).

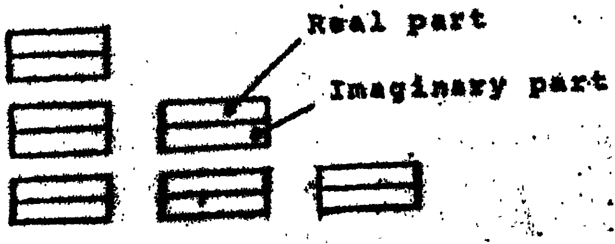
(b) Line Constants

Since all matrices are symmetric, only values in and below the diagonal are printed:



this "lower triangular" matrix is printed only.

All matrices, except the susceptance (or capacitance) matrices for the physical and equivalent conductors, are complex. Real and imaginary parts are printed right above each other:



The matrix elements of the impedance matrices per mile are defined as follows:

$z'_{i,k}$ = mutual impedance between i and k,

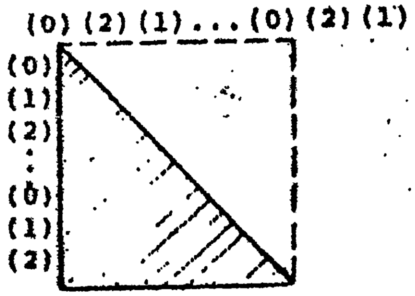
$z'_{i,i}$ = self impedance of i.

The matrix elements of the susceptance (or capacitance) matrices per mile are defined as follows:

$\omega C'_{i,k}$ = negative value of susceptance between i and k,

$\omega C'_{i,i}$ = sum of all susceptances from i to all other conductors and to ground.

Note that the matrices for symmetrical components have the rows ordered in the sequence "zero (0), positive (1), negative (2) of 1st circuit, (0), (1), (2) of 2nd circuit etc.", whereas the columns have (1) and (2) exchanged and are thus ordered "(0), (2), (1) of 1st circuit, (0), (2), (1) of 2nd circuit etc.". This makes these matrices symmetric:



From this row-and column numbering it follows that

$z'_{1,1} = z'_{2,2}$ within any 3-phase circuit

$z'_{1,0} = z'_{0,2}$ within any 3-phase circuit

etc.

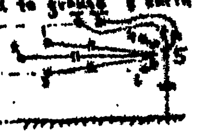
If the line is transposed, then assume all couplings between sequences to be zero, except between zero sequences of parallel circuits (see section 5). Note that the capacitive couplings between sequences of the untransposed lines are complex (this is why the susceptance or capacitance matrices per mile for symmetrical components are printed complex with an imaginary part which is zero in terms that do not couple sequences).

If the user asks for the susceptance (or capacitance) and impedance matrices per mile for symmetrical components, then additional sequence parameters are printed for the first 3-phase circuit (see attached output sheets). This output is primarily intended for single 3-phase and 2-phase circuits.

```
TEST EXAMPLE FROM M. D. HESSE, TRANSLATED ...                          JAN-22-69

RECORD OF SORTED INPUT DATA
  PHASE NUMBER R-TYPE RESISTANCE X-TYPE T OR GMR DIAMETER X-COORD. Y-COORD.   NAME
   1      1     -0.    0.08510     1    0.36500  1.46500   1.000   120.000   PH-A 1
   2      2     -0.    0.08510     1    0.36500  1.46500   0.       85.000   PH-B 1
   3      3     -0.    0.08510     1    0.36500  1.46500   7.000    50.000   PH-C 1
   4      4     -0.    0.08510     1    0.36500  1.46500  52.500   120.000   PH-A 2
   5      5     -0.    0.08510     1    0.36500  1.46500  61.000    85.000   PH-B 2
   6      6     -0.    0.08510     1    0.36500  1.46500  56.000    50.000   PH-C 2
   7      1     -0.    0.08510     1    0.36500  1.46500   8.500   120.000   NU 7
   8      2     -0.    0.08510     1    0.36500  1.46500   1.500    85.000   NU 8
   9      3     -0.    0.08510     1    0.36500  1.46500   4.500    50.000   NU 9
  10      6     -0.    0.08510     1    0.36500  1.46500  55.500    50.000   NU10
  11      5     -0.    0.08510     1    0.36500  1.46500  63.500    85.000   NU11
  12      4     -0.    0.08510     1    0.36500  1.46500  58.500   120.000   NU12
  13      0     -0.    0.58800     1    0.44400  0.57700   2.400   140.000   NU13
  14      0     -0.    0.58800     1    0.44400  0.57700  65.000   140.000   NU14

FOLLOWING MATRICES ARE FOR EARTH RESISTIVITY=  100.00 OHM-M AND FREQUENCY=    60.00 HZ.    CORRECTION FACTOR=  0.000001

            SUSCEPTANCE MATRIX (MHO/MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
                   ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

 1   0.61894E-05
 2  -0.10404E-05   0.61368E-05
 3  -0.33335E-06  -0.10287E-05   0.62730E-05
 4  -0.67823E-06  -0.38319E-06  -0.17888E-06   0.61894E-05
 5  -0.38310E-06  -0.19163E-06  -0.32754E-06  -0.10404E-05   0.61368E-05
 6  -0.17888E-06  -0.32754E-06  -0.53841E-06  -0.33335E-06  -0.10287E-05   0.62730E-05

            SUSCEPTANCE MATRIX (MHO/MILE) FOR THE SYMMETRICAL COMPONENTS OF THE EQUIVALENT PHASE CONDUCTORS
            ROWS PROCEED IN SEQUENCE 0,1,2, 0,1,2 ETC. AND COLUMNS PROCEED IN SEQUENCE 0,2,1, 0,2,1 ETC.

 0   0.45646E-05
     0.
 1   0.10050E-06  -0.21615E-06
    -0.25797E-06  -0.39801E-06
 2   0.10050E-06   0.70175E-05  -0.21615E-06
     0.25797E-06  -0.41310E-14   0.39801E-06
 0  -0.11423E-05  -0.58853E-07  -0.58853E-07   0.45646E-05
    -0.           -0.12019E-07   0.12019E-07   0.
 1  -0.58853E-07  -0.45409E-07  -0.23294E-06   0.10050E-06  -0.21615E-06
    -0.12019E-07  -0.15767E-06  -0.53291E-14  -0.25797E-06  -0.39801E-06
 2  -0.58853E-07  -0.23294E-06  -0.45409E-07   0.10050E-06   0.70175E-05  -0.21615E-06
     0.12019E-07   0.53291E-14   0.15767E-06   0.25797E-06  -0.29485E-14   0.39801E-06

            IMPEDANCE MATRIX (OHM/MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
                   ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

 1   0.14023E 00
     0.83585E 00
 2   0.96591E-01   0.12274E 00
     0.28784E 00   0.91539E 00
 3   0.91076E-01   0.80064E-01   0.11647E 00
     0.22969E 00   0.34299E 00   0.95186E 00
 4   0.94482E-01   0.93538E-01   0.84986E-01   0.14023E 00
     0.21231E 00   0.21452E 00   0.20575E 00   0.83585E 00
 5   0.93538E-01   0.87118E-01   0.85531E-01   0.96591E-01   0.12274E 00
     0.21452E 00   0.25218E 00   0.26538E 00   0.28784E 00   0.91539E 00
 6   0.84986E-01   0.85531E-01   0.83384E-01   0.91076E-01   0.80064E-01   0.11647E 00
     0.20575E 00   0.26538E 00   0.31403E 00   0.22969E 00   0.34299E 00   0.95186E 00

            IMPEDANCE MATRIX (OHM/MILE) FOR THE SYMMETRICAL COMPONENTS OF THE EQUIVALENT PHASE CONDUCTORS
            ROWS PROCEED IN SEQUENCE 0,1,2, 0,1,2 ETC. AND COLUMNS PROCEED IN SEQUENCE 0,2,1, 0,2,1 ETC.

 0   0.30887E 00
     0.14747E 01
 1   0.32497E-02  -0.42373E-01
    -0.53344E-01   0.25004E-01
 2   0.13797E-01   0.35143E-01   0.45882E-01
```

negative value of susceptance between 4th & 2nd equiv. conductors ($\omega C_{4,2} = 0.3831$ μmho/mile)

Sum of all susceptances from 5th equiv. conductor to all other equiv. conductors and to ground & earth wires (see FIG.)



Column labels: 0 2 1 0 2 1

1st 3-phase circuit

2nd 3-phase circuit

zero-sequence susceptance of 1st 3-phase-circuit (phases 1,2,3)

positive-seq. susceptance " " "

zero-sequence susceptance of 2nd 3-phase-circuit (phases 4,5,6)

positive seq.

negative value of zero-seq. & pos.seq. susceptance between 1st and 2nd circuit

mutual impedance between 4th & 3rd equiv. conductors ($Z_{4,3}$ = 0.084986 + j 0.20575 Ω/mile)

self impedance of 5th equiv. conductor

zero-sequence impedance of 1st circuit

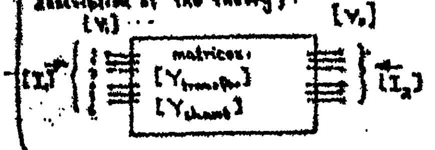
```
                                                                     0.69589C-01
                                                                     0.22061E-01
                                                        [illegible]ION   VELOCITY     WAVELENGTH
                                                        [illegible]      MILES/S      MILES
 [illegible]                                           [illegible]-02   0.144532E 06  0.240R7E 04
ZERO      0.3 558E 03 -0.[illegible]01  0.[illegible]  [illegible] 02  0.234731-02  0.144532E 06  0.240R7E 04
POSITIVE  0.2496E 03 -0.16331E 01  0.29546E 03 -0.05890E 01  0.315696-03  0.181512E 06  0.302531E 04
```

} additional sequence parameters for the 3-phase-circuit (output intended for single 3-phase-circuits)

```
MATRICES FOR LINE LENGTH= 200.000 MILES, COMPUTED BY CONNECTING IN SERIES 2** 4 EQUAL SECTIONS OF  12.5000 MILES EACH.

         TRANSFER ADMITTANCE MATRIX (MHOS) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
                 ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

 1   0.626445E-01
    -0.730653E-02

 2  -0.777631E-05   0.431212E-01
     0.354441E-02  -0.724421E-02

 3   0.541214E-04  -0.741110E-04   0.384048E-03
     0.706491E-03   0.187471E-02  -0.446741E-02

 4   0.443482E-04   0.417941E-04   0.411478E-04   0.476443E-03
     0.147233E-02   0.451196E-03   0.566728E-03  -0.730416E-02

 5   0.612458E-04   0.221718E-04   0.157948E-04  -0.377648E-05   0.431212E-03
     0.651445E-03   0.692052E-03   0.744148E-03   0.135443-02  -0.724491E-02

 6   0.411472E-04   0.157948E-04  -0.160408E-04   0.531218E-04  -0.741110E-04   0.380048E-03
     0.560728E-03   0.744198E-03   0.128155E-02   0.106058E-03   0.187478E-02  -0.440348E-02
```

$Y_{transfer\,3,2} = -0.406674R+j0.0016747$ mho

These matrices define the 200-mile untransposed line for 60 Hz steady-state with eq.(3) (see short description of the theory):

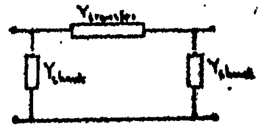


$$\begin{bmatrix}[Y_{transfer}]+[Y_{shunt}] & -[Y_{transfer}]\\ -[Y_{transfer}] & [Y_{transfer}]+[Y_{shunt}]\end{bmatrix}\begin{bmatrix}[V_1]\\ [V_2]\end{bmatrix}=\begin{bmatrix}[I_1]\\ [I_2]\end{bmatrix}$$

```
          SHUNT ADMITTANCE MATRIX (MHOS) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
                 ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

 1   0.959122E-06
     0.679146E-03

 2   0.216758E-06   0.120148E-06
    -0.111258E-03   0.623095E-03

 3   0.491221E-06   0.195476E-06   0.869278E-06
    -0.131468E-04  -0.143448E-03   0.637818E-03

 4   0.355722E-06   0.242946E-06   0.404558E-06   0.100706E-05
    -0.645148E-04  -0.285127E-04  -0.145448E-04   0.628126E-03

 5   0.291468E-06   0.215468E-06   0.245178E-06   0.219368E-06   0.716494E-06
    -0.345838E-04  -0.395795E-04  -0.324328E-04  -0.110758E-03   0.622928E-03

 6   0.404478E-06   0.245746E-06   0.154058E-06   0.401468E-06   0.195578E-06   0.897288E-06
    -0.195468E-04  -0.324338E-04  -0.529918E-04  -0.331938E-04  -0.103468E-03   0.637428E-03
```

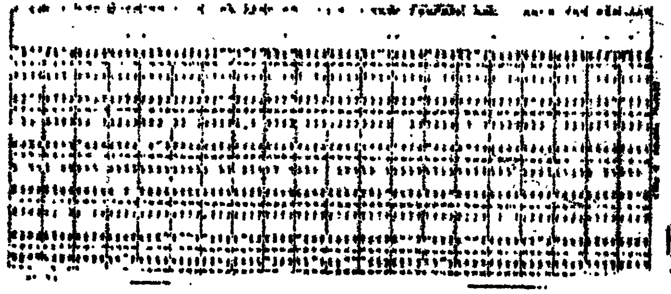
$Y_{shunt\,3,3} = 0.000\,000\,86927+j\,0.000\,63781$ mho

Equivalent circuit for a single phase line



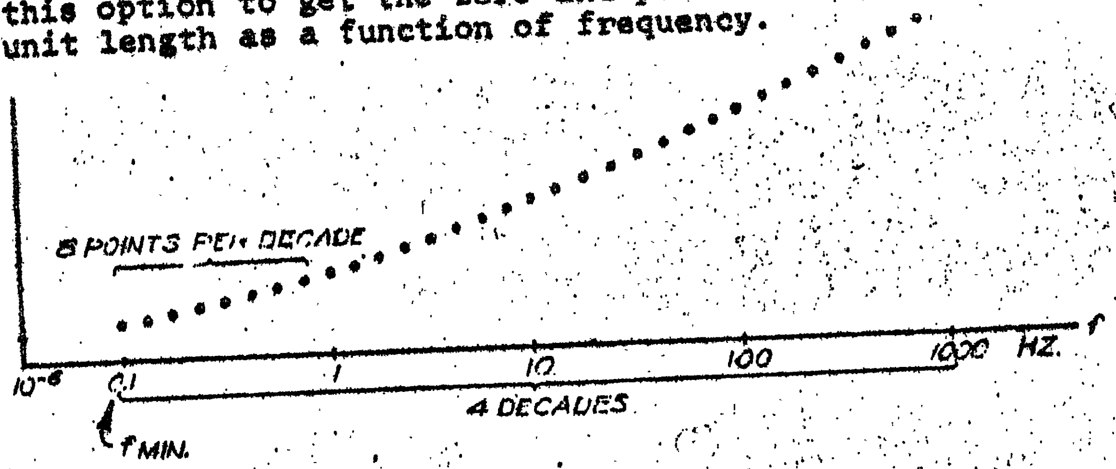
```
   100       60              1      11  11       200     1

   0       5430  1   484    577     45    160     130   MO14
   0       3060  1   484    577      7    160     130   MO13
   4       6457  1   365   1463    585    148     110   MO12
   3       6457  1   365   1463    635    105      75   MO11
   2       6457  1   365   1463    385     70      40   MO10
   3       6457  1   365   1463     85     70      40   MO 9
   2       6457  1   365   1463     15    105      75   MO 8
   1       6457  1   365   1465     35    140     110   MO 7
   4       6457  1   365   1465     40     70      40   PH-C 2
   3       6457  1   365   1465     47    105      75   PH-B 2
   2       6457  1   365   1465     40    140     110   PH-A 2
   2       6457  1   365   1465      0    105      75   PH-B 1
   3       6457  1   365   1465      7     70      40   PH-C 1
   2       6457  4   365   1465      7    140     110   PH-A 1
TEST EXAMPLE FROM H. H. HESSE, TRANS.AIEE III VOL.82(1963), PAGE 283.   JAN-28-65
```

DATA DECK FOR TEST EXAMPLE



Special Output for Frequency Dependence of Zero and Positive Sequence Parameters

Use this option to get the zero and positive sequence parameters per unit length as a function of frequency.



The values are computed at equidistant points on a logarithmic frequency scale, with f = 0 approximated by 10^{-6} Hz. Punch

f_{min} in col. 9-18

no. of decades in col. 60-62

no. of points per decade in col. 63-65

IPUNCH in col. 66-68 ** (not yet available)

} on the frequency card

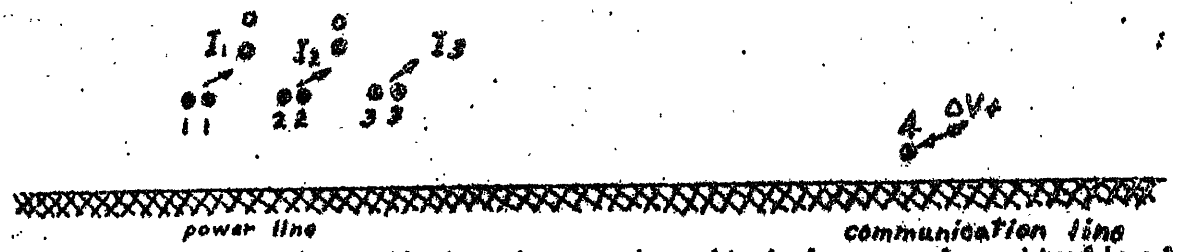
Earth resistivity (col. 1-8), earth return correction (col. 19-28), ground wire segmentation (col. 58), and the output options in columns 30-35, 37-42, and 54-57 retain their meaning as for the conventional, single-frequency case. All other parameters on the frequency card are ignored. To obtain a nice table output (of zero and positive-sequency parameters as a function of frequency), however, leave columns 30-35 and 37-42 blank; otherwise, the requested matrices will be printed between the lines of the table output.

IPUNCH = 0 or blank: The program will print the parameters α(neper/mile), β(radian/mile), R(Ω/mile), L(mH/mile) and C(μF/mile) for zero and positive sequence as a function of frequency.

IPUNCH > 0: In addition to printing, the parameters α_0, β_0, (zero sequence), α_1, β_1 (positive sequence) and f (Hz) are also punched on cards with the format 5E15.5.

The cards are intended to be used as input for transients programs which can handle the frequency dependence. At this time, only the FOURIER TRANSFORMATION program can accept the frequency dependence (directly in the form of these cards).

Special Output for Mutual Impedance Between a 3-Phase Circuit and a Communication Line



Currents in a three-phase circuit induce a longitudinal voltage in the communication line no. 4, (the three-phase circuit may have bundle conductors and earth wires). The induced voltage is

$$\Delta V_4 = Z'_{41} I_1 + Z'_{42} I_2 + Z_{43} I_3 \qquad (1)$$

If the phase currents are transformed to un-normalized sequence quantities (see p. 28),

$$\begin{bmatrix} I_{zero} \\ I_{positive} \\ I_{negative} \end{bmatrix} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}, \text{ with } a = e^{j120^\circ} \qquad (2)$$

then $\Delta V_4 = Z'_{zero/4} \cdot I_{zero} + Z'_{positive/4} \cdot I_{positive} + Z'_{negative/4} \cdot I_{negative}$ (3a)

$$\text{with} \quad \left.\begin{aligned} Z'_{zero/4} &= Z'_{41} + Z'_{42} + Z'_{43} \\ Z'_{positive/4} &= Z'_{41} + a^2 Z'_{42} + a\, Z'_{43} \\ Z'_{negitive/4} &= Z'_{41} + a\, Z'_{42} + a^2 Z'_{43} \end{aligned}\right| \quad (3b)$$

The absolute values of these mutual impedances will be printed. Note that these values would have to be multiplied $\sqrt{3}$ if normalized sequence quantities were used.

How to Obtain Special Output:

FORMAT OF SPECIAL OUTPUT:

```
Mutual Impedance    Positive = .00008 ohm/mile
                    Negative = .00007 ohm/mile
                    Zero     = .0209 ohm/mile
```

(1) The phases must be numbered 1, 2, 3 (bundles and earth wires permitted); the communication line must be no. 4.

(2) Punch "1" in column 59 of the frequency card.

The mutual impedances of eq. (3b) as well as the impedance matrix for the equivalent phase conductors are printed, in addition to any other output requested. If the number of equivalent pha conductors is unequal 4, then the special output is skipped (all other requested output will still be correct) and the following message is printed:

SPECIAL OUTPUT FOR MUTUALS NOT APPLICABLE TO THIS CASE

II PROGRAM DESCRIPTION

1. INTRODUCTION

The line parameters of overhead transmission lines are necessary input data for more or less detailed studies of transmission line phenomena. The simplest constants are the series impedance and shunt capacitance for the positive sequence as used in power flow studies. These are usually available from tables. Often more detailed line parameters, not available from tables, are needed. Examples can be grouped according to the nature of the phenomena:

(a) Steady-state problems at power frequency. As examples, one may want to study the current and voltage dissymmetry on a long, untransposed line or the unequal current distribution among the individual conductors of a bundle conductor. Another example is the investigation of induced voltages and currents in a de-energized line running parallel with an energized line (very important for the safety of maintenance crews).

(b) Steady-state problems at higher frequencies. Typical studies are interference in neighboring communication lines, propagation of harmonics on an HVDC line and carrier communication on power lines.

(c) Transients problems. Typical studies are switching surges and lightning surges and means of reducing them with protective gaps, lightning arresters, insertion of resistors in circuit breakers etc.

Line parameters could be measured after the line has been built. However, some of them are already needed in the design stage; therefore, they must be computed beforehand. Even after the line has been built, it is easier to compute the parameters with sufficient accuracy.

The following notes explain the basic formulas used in the digital computation of line parameters. Computer programs should be as general as possible, that is they should allow for any number of conductors of which some may be bundled and others grounded, and for any frequency and ground resistivity. The theory for such programs is scattered in many papers and is seldom found in textbooks because most of them are still geared to hand computations with special formulas for each particular case. A good summary is the paper by M.H. Hesse [2].

2. LINE PARAMETERS FOR PHYSICAL CONDUCTORS

Fig.1 shows the tower configuration of two parallel three-phase circuits with twin bundle conductors and one ground wire. There are 13 conductors in this configuration. They will be called physical conductors to distinguish them from the 6 equivalent phase conductors which are obtained after pairs have been bundled into phase conductors and after the ground wire has been eliminated from the associated equations.

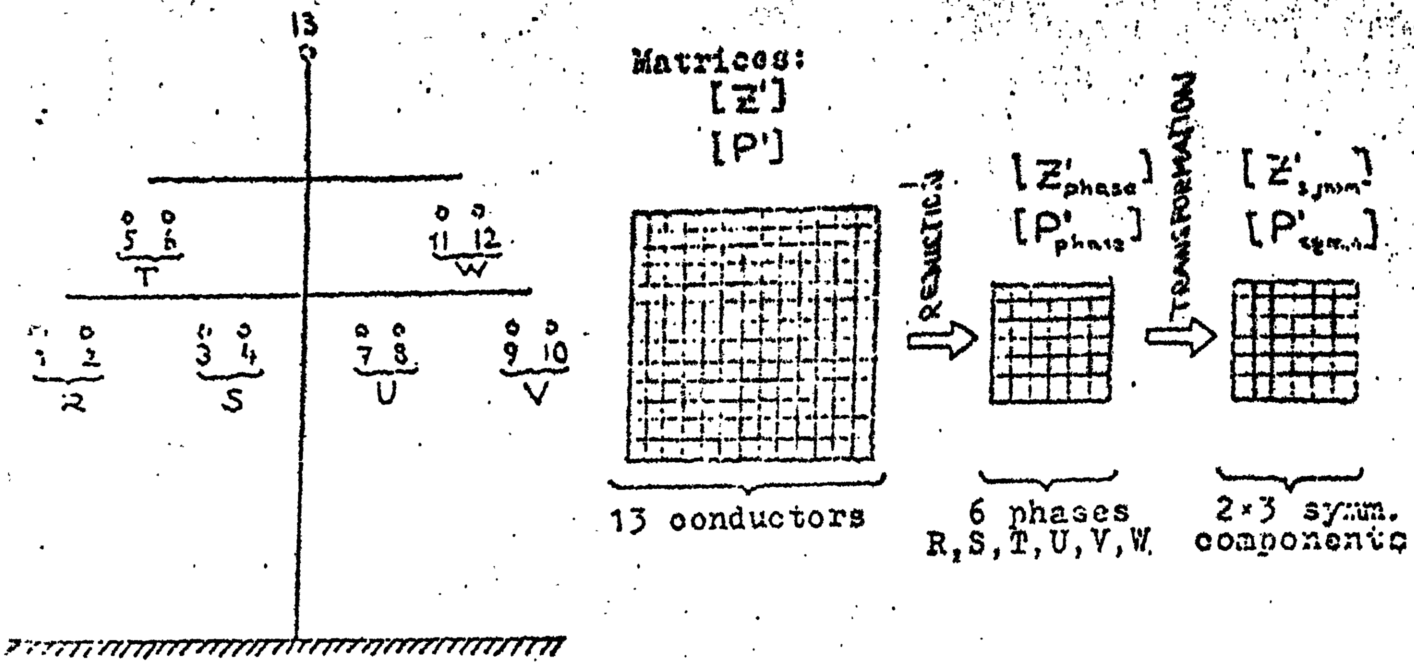


Fig.1 Line parameters

2.1 Series impedance

The voltage drop along these 13 conductors is a function of the currents. For ac steady-state conditions, phasors can be used to express this voltage drop (negative sign on left hand indicates drop): *)

$$-\begin{bmatrix} \frac{dV_1}{dx} \\ \frac{dV_2}{dx} \\ \vdots \\ \frac{dV_{13}}{dx} \end{bmatrix} = \begin{bmatrix} Z'_{11} & Z'_{12} & \dots & Z'_{1,13} \\ Z'_{21} & Z'_{22} & \dots & Z'_{2,13} \\ \dots & \dots & \dots & \dots \\ Z'_{13,1} & Z'_{13,2} & \dots & Z'_{13,13} \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_{13} \end{bmatrix} \qquad (1a)$$

with V_i = voltage (phasor) from conductor i to ground,
I_i = current (phasor) in conductor i,

or in the general case

$$-\left[\frac{dV}{dx}\right] = [Z'][I] \qquad (1b)$$

with $[V]$ = vector of conductor voltages,
$[I]$ = vector of conductor currents.

$[Z'] = [R'] + j\omega [L']$ is called the series impedance matrix; it is complex and symmetric. The diagonal element $Z'_{ii} = R'_{ii} + j\omega L'_{ii}$ is the series self impedance per unit length of the loop formed by conductor i and ground.

---

*) Primed letters are used to indicate quantities per unit length Brackets are used to indicate matrices and vectors.

return. The off-diagonal element $Z'_{ik} = Z'_{ki} = R'_{ki} + j\omega L'_{ki}$ is the series mutual impedance per unit length between conductors i and k. It may be surprising to find resistive terms in the mutual coupling. They are introduced by the presence of ground and describe the phase shift which takes place in the coupling. All elements are calculated with Carson's formula, which assumes that the earth has uniform conductivity and is bounded by a flat plane with infinite extent. The details are explained in appendix 1a. The formulas in most textbooks are derived from Carson's work by retaining only the first one or two terms in an infinite series. This is acceptable at power frequency and for normal conductor spacings. At higher frequencies and for wider spacings, however, (e.g., in interference calculations) these formulas would produce very severe errors. Therefore, a general purpose program must have a provision to use many more terms in the infinite series. This is also explained in appendix 1a.

The elements of the series impedance matrix are computed from the geometry of the tower configuration and from certain characteristics of the conductors (resistance and internal inductance or geometric mean radius). Conductor resistance and internal inductance change with frequency due to skin effect. Therefore, a formula for skin effect correction is needed. Appendix 2 explains the skin effect formula for tubular conductors, which also covers the solid conductor, with a detailed description of the subroutine SKIN. Stranded conductors can be approximated by a solid conductor of identical cross-section. Steel-reinforced aluminum cables could be handled as tubular conductors with the steel core ignored. Note, however, that these approximations may not be valid at high frequencies where more accurate formulas may be needed. A case study of this problem is shown in appendix 3.

2.2 Shunt capacitance

The voltages of the 13 conductors (measured to ground) are a function of the line charges. For ac steady state conditions the relationship is

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_{13} \end{bmatrix} = \begin{bmatrix} P'_{11} & P'_{12} & \dots & P'_{1,13} \\ P'_{21} & P'_{22} & \dots & P'_{2,13} \\ \dots & \dots & \dots & \dots \\ P'_{13,1} & P'_{13,2} & \dots & P'_{13,13} \end{bmatrix} \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_{13} \end{bmatrix} \qquad (2a)$$

with Q_i = charge (phasor) on conductor per unit length,

or in the general case

$$[V] = [P'][Q] \qquad (2b)$$

The elements of Maxwell's potential coefficient matrix $[P']$ are computed from the geometry of the tower configuration and the conductor radii as explained in appendix 1b. The matrix $[P']$ is symmetric and real. The inverse relationship

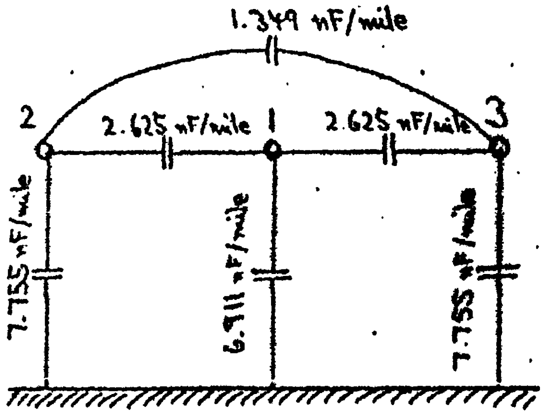
$$[Q] = [C'][V] \qquad (3)$$

uses the capacitance matrix, which is the inverse of the potential coefficient matrix:

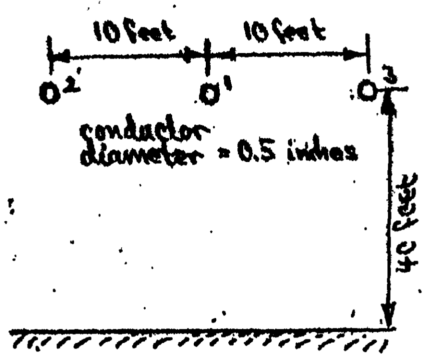
$$[C'] = [P']^{-1} \tag{4}$$

A suitable inversion technique is the Gauss-Jordan process for matrix inversion with advantage taken of the symmetry [3]. This process can easily be modified to handle matrix reductions as well, which is needed later for eliminating ground wires and for bundling conductors. Appendix 4 describes the subroutine for matrix reduction or inversion.

The capacitance matrix $[C']$ is in nodal form. This means that the diagonal element C'_{ii} is the sum of the shunt capacitances per unit length between conductor i and all other conductors and ground, the off-diagonal element $C'_{ik} = C'_{ki}$ is the negative shunt capacitance per unit length between conductors i and k. Example for a 3-phase circuit [6]:



obtained from the following data:



$$[C'] = \begin{bmatrix} 1.2161 & -0.2625 & -0.2625 \\ -0.2625 & 1.1729 & -0.1349 \\ -0.2625 & -0.1349 & 1.1729 \end{bmatrix} \cdot 10^{-8} \text{ F/mile}$$

For steady state conditions, the vector of charges (as phasors) is related to the vector of leakage currents $[-\frac{dI}{dx}]$ by

$$[Q] = -\frac{1}{j\omega}\left[\frac{dI}{dx}\right] \tag{5}$$

Therefore, the second system of differential equations is

$$-\left[\frac{dI}{dx}\right] = j\omega [C'][V] \tag{6}$$

The matrices for all physical conductors are an ideal tool for studying unbalanced current distribution in bundle conductors [21].

3. ELIMINATION OF GROUND WIRES AND BUNDLING OF CONDUCTORS

The equations (1a) and (2a) for all 13 conductors contain mor information than is usually wanted. Generally, only the phase quantities are of interest (in Fig. 1 phases R,S,T and U,V,W). The transition from two systems with 13 equations to those with 6 equations for the phase quantities is accomplished by introducing the terminal conditions, in Fig. 1,

for grounding 13: $\frac{dV_{13}}{dx} = 0$ in (1), $V_{13} = 0$ in (2),

for bundling 1,2 into phase R: $I_1 + I_2 = I_R$, $\frac{dV_1}{dx} = \frac{dV_2}{dx} = \frac{dV_R}{dx}$ in (1), and
$Q_1 + Q_2 = \underline{Q_R}$, $V_1 = V_2 = V_R$ in (2),

etc. The reduced matrices (in Fig. 1, 6 x 6 matrices) are often called matrices for the equivalent phase conductors.

3.1 Bundling of conductors

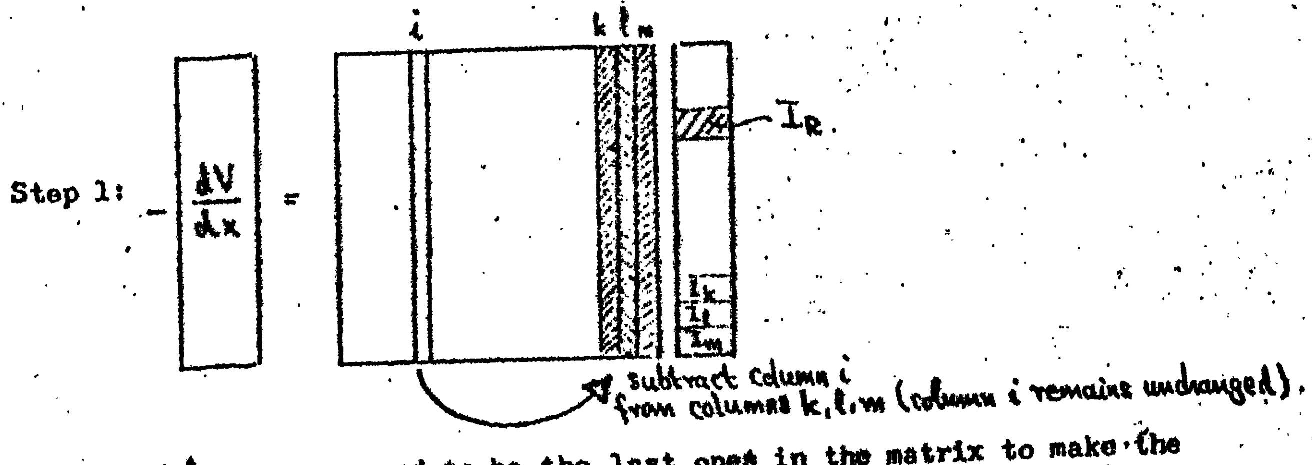
The mathematical process which reflects bundling is analogous for the system of equations (1) and (2). Therefore, it will only be shown for q (1). Let us assume that conductors i,k,l,m are to be bundled to form phase R. Then the terminal conditions

$$I_i + I_k + I_l + I_m = I_R$$

and
$$\frac{dV_i}{dx} = \frac{dV_k}{dx} = \frac{dV_l}{dx} = \frac{dV_m}{dx} = \frac{dV_R}{dx}$$

must be introduced into (1). The first step is to get I_R into the equations. This is done by writing I_R in place of I_i. By doing this, terms of the form
$$Z'_{\mu i}(I_k + I_l + I_m)$$

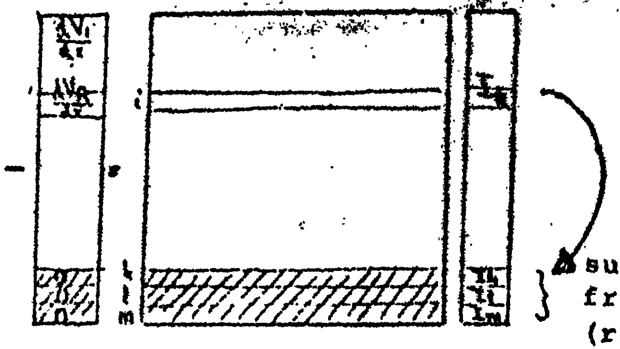
are added in any one row μ; they must be subtracted again to keep the equations valid. In effect, this means subtraction of column i from columns k,l,m. The changes are indicated by shading:


Step 1:
$-\frac{dV}{dx}$
=
i
k
l
m
I_R
I_k
I_l
I_m
subtract column i from columns k,l,m (column i remains unchanged).

Columns k,l,m are assumed to be the last ones in the matrix to make the explanation easier. The currents I_k, I_l, I_m are still in the equations. To eliminate them, there should be zeros in the respective rows of the left hand side. This is accomplished by **subtracting row i from rows k, l, m.** Zero is produced because $\frac{dV_i}{dx} = \frac{dV_k}{dx}$

etc. Again, the changes are indicated byy shading:

Step 2 :
(after step 1 has
been performed)



subtract row i
from rows k, l, m
(row i remains unchanged!

The equations are now in a form which permits elimination of I_k, I_l, I_m as explained in appendix 4.

3.2 Elimination of ground wires

Again, the mathematical process is analogous for the system of eq. (1) and (2) so that it suffices to show it for eq. (1) only. Let us assume that conductor j is a ground wire. In contrast to bundling, no preparatory work is necessary for elimination of ground wires because the matrix already has the form required for elimination (left hand side $\frac{dV_j}{dx} = 0$!). The assumption $\frac{dV_j}{dx} = 0$ is correct as long as the ground wire is grounded at distances much shorter than the wave length so that no potential can build up in the wires. At power frequency this assumption is always true. At very high frequencies, e.g. in lightning surge studies, this may not be true any more. In such cases the ground wires should not be eliminated.

3.3 Reduced system for equivalent phase conductors

When step 2 of section 3.1 has been completed for all bundle conductors and when all ground wires and second, third,... conductors of bundles have been placed in the last rows and columns, then the equations will have the form

$$\begin{bmatrix} -\left[\frac{dV_{phase}}{dx}\right] \\ \cdots\cdots \\ 0 \end{bmatrix} = \begin{bmatrix} [Z'_{phase,phase}] & [Z'_{phase,rest}] \\ [Z'_{rest,phase}] & [Z'_{rest,rest}] \end{bmatrix} \begin{bmatrix} [I_{phase}] \\ \cdots\cdots \\ [I_{rest}] \end{bmatrix}$$

non-bundled conductors and first conductor in each bundle

rest of conductors (ground wires, plus second, third, ... conductor in each bundle

After eliminating $[I_{rest}]$ as explained in appendix 4, the reduced system for the equivalent phase conductors

$$-\left[\frac{dV_{phase}}{dx}\right] = \left[Z'_{phase}\right]\left[I_{phase}\right] \qquad (7)$$

is obtained, with $[Z'_{phase}] = [Z'_{phase,phase}] - [Z'_{phase,rest}][Z'_{rest,rest}]^{-1}[Z'_{rest,phase}]$.

For Fig. 1 , this process reduces the 13 x 13 matrix for the physical conductors to a 6 x 6 matrix for the phases. In this example, the phase equations would be:

$$-\frac{d}{dx}\begin{bmatrix} V_R \\ V_S \\ V_T \\ V_U \\ V_V \\ V_W \end{bmatrix} = \begin{bmatrix} Z'_{RR} & Z'_{RS} & Z'_{RT} & Z'_{RU} & Z'_{RV} & Z'_{RW} \\ Z'_{SR} & Z'_{SS} & Z'_{ST} & Z'_{SU} & Z'_{SV} & Z'_{SW} \\ Z'_{TR} & Z'_{TS} & Z'_{TT} & Z'_{TU} & Z'_{TV} & Z'_{TW} \\ Z'_{UR} & Z'_{US} & Z'_{UT} & Z'_{UU} & Z'_{UV} & Z'_{UW} \\ Z'_{VR} & Z'_{VS} & Z'_{VT} & Z'_{VU} & Z'_{VV} & Z'_{VW} \\ Z'_{WR} & Z'_{WS} & Z'_{WT} & Z'_{WU} & Z'_{WV} & Z'_{WW} \end{bmatrix} \cdot \begin{bmatrix} I_R \\ I_S \\ I_T \\ I_U \\ I_V \\ I_W \end{bmatrix}$$

For a three-phase single circuit with phases A,B,C, eq. (7) would have form

$$-\begin{bmatrix} \frac{dV_A}{dx} \\ \frac{dV_B}{dx} \\ \frac{dV_C}{dx} \end{bmatrix} = \begin{bmatrix} Z'_{AA} & Z'_{AB} & Z'_{AC} \\ Z'_{BA} & Z'_{BB} & Z'_{BC} \\ Z'_{CA} & Z'_{CB} & Z'_{CC} \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

The diagonal element Z'_{KK} is the series self impedance of phase K for the loop formed by phase K and ground return and the off-diagonal element Z'_{IK} is the series mutual impedance between phases I and K. The self impedance of phase K is not the positive sequence impedance. If we assume symmetric operation in a three-phase single circuit, then the currents are

$$I_B = a^2 I_A \text{ and } I_C = a\, I_A \text{ with } a = e^{j120^\circ}$$

This gives

$$-\frac{dV_A}{dx} = \underbrace{(Z'_{AA} + a^2 Z'_{AB} + a Z'_{AC})}_{Z_1} I_A \qquad (8)$$

where Z_1 is the positive sequence impedance describing the normal symmetric operation of phase A. Eq. (8) is the single-phase representation of symmetric three-phase operation.

All derivations in sections 3.1 to 3.3 were carried out for eq. (1). As already mentioned, analogous derivations must be carried out for eq. (2) with the following correspondence:

[V] in (2) takes the place of $-\left[\frac{dV}{dx}\right]$ in (1),

] in (2) takes the place of [Z'] in (1),

] in (2) takes the place of [I] in (1).

that the process of bundling and ground wire elimination must be lied to [P'] rather than to [C']. If the capacitance matrix for the phases $[C'_{phase}]$ is desired, one finds $[P'_{phase}]$ first and then inverts this smaller matrix.

The reduced matrices for the phases are an ideal tool for studying unbalances in the phases if the line is not transposed, at power frequency as well as for switching surges.

INDEPENDENT MODES

In what follows it is assumed that the line is not transposed or that the length of a transposition cycle is not much shorter than the wave length. This is always true at high frequencies. Therefore, the following techniques are primarily used for radio frequency problems.

Currents and voltages in the phases at one frequency are related by two systems of differential equations,

$$-\left[\frac{dV_{phase}}{dx}\right] = [Z'_{phase}]\cdot[I_{phase}] \qquad (9)$$

$$-\left[\frac{dI_{phase}}{dx}\right] = [Y'_{phase}]\cdot[V_{phase}] \qquad (10)$$

$$\text{with } [Y'_{phase}] = j\omega[C'_{phase}]$$

It is customary to neglect shunt conductances due to leakage and corona so that the shunt admittance is equal to the shunt susceptance. Eq. (9) and (10) are valid for phasors as well as for the Fourier transforms if phenomena with many frequencies are studied.

By differentiating (9) with respect to x and inserting the result into (10) a second-order differential equation is obtained for the voltages only,

$$\left[\frac{d^2V_{phase}}{dx^2}\right] = [Z'_{phase}][j\omega C'_{phase}][V_{phase}] \qquad (11)$$

Similarly, a second system of equations is obtained for the currents,

$$\left[\frac{d^2I_{phase}}{dx^2}\right] = [j\omega C'_{phase}][Z'_{phase}][I_{phase}] \qquad (12)$$

Generally, the two matrix products $[Z'_{phase}][j\omega C'_{phase}]$ and $[j\omega C'_{phase}][Z'_{phase}]$ are different because multiplication in matrix algebra is not commutative.

Eq. (11) and (12) are difficult to solve because all phases are coupled, or mathematically, the matrix products have off-diagonal elements. It is possible, however, to transform the phase quantities into "modal" quantities $[V_{mode}]$ and $[I_{mode}]$ in such a way that the associated matrices are diagonal,

$$\left[\frac{d^2V_{mode}}{dx^2}\right] = \underbrace{[\Lambda]}_{\text{diagonal matrix}}[V_{mode}] \qquad (13)$$

In the mode domain the system of M equations breaks down into M independent (decoupled) equations. Each mode can then be solved in the same way as a single phase line. The phase quantities are changed to mode quantities and vice versa with a linear transformation. For the voltages this is

$$[V_{phase}] = [S][V_{mode}] \qquad (14)$$

and $$[V_{mode}] = [S]^{-1}[V_{phase}].$$

Then eq. (11) becomes

$$\left[\frac{d^2V_{mode}}{dx^2}\right] = [S]^{-1}\left\{[Z'_{phase}][j\omega C'_{phase}]\right\}[S][V_{mode}] \qquad (15)$$

or $$[\Lambda] = [S]^{-1}[Z'_{phase}][j\omega C'_{phase}][S]$$

To find the matrix $[S]$ which diagonalizes $[Z'_{phase}][j\omega C'_{phase}]$ is a fundamental problem in matrix algebra. There are standard techniques available for doing this. An efficient algorithm for finding the eigenvalues λ_i, which are the diagonal elements of $[\Lambda]$,

$$[\Lambda] = \begin{bmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \lambda_3 & \\ & & & \ddots & \\ & & & & \lambda_M \end{bmatrix},$$

is the QR transformation due to Francis [8]. Once the eigenvalues are known, the matrix $[S]$ is found by solving the equations

$$\left([Z'_{phase}][j\omega C'_{phase}] - \begin{bmatrix} \lambda_i & & & \\ & \lambda_i & & \\ & & \ddots & \\ & & & \lambda_i \end{bmatrix}\right)\cdot[S_i] = 0 \qquad (16)$$

for $[S_i]$. These columns are called "eigenvectors"; they are identical with the columns of the transformation matrix $[S]$. Eq. (16) can usually be solved by setting one component of $[S_i]$ arbitrarily to 1.0 and solving for the rest of the components. If this process does not work, then an efficient algorithm for finding the eigenvectors for given eigen- values is the inverse iteration scheme due to Wilkinson [9]. The transformation matrix [S] is not uniquely defined. Each column of it can be multiplied with a constant.

In general, a different transformation must be used for the currents:*

$$[I_{phase}] = [T][I_{mode}]$$

and

$$[I_{mode}] = [T]^{-1}[I_{phase}] \qquad (17)$$

because the matrix products in (11) and (12) have different eigenvectors. Their eigenvalues are identical, though. However, $[T]$ can easily be found from $[S]$ with

$$[T] = [C'_{phase}][S] \qquad (18)$$

where $[T]$ would be unnormalized. It could be normalized by first adding the squares of all elements in a column and taking the square root of this sum,

$d_k = \sqrt{\sum_{i=1}^{M} t_{ik}}$, and then dividing each element in that column by d_k.

If

$$[D] = \begin{bmatrix} d_1 & & & & \\ & d_2 & & & \\ & & d_3 & & \\ & & & \ddots & \\ & & & & d_M \end{bmatrix}$$

then

$$[T]_{normalized} = [T]\cdot[D]^{-1} \qquad (19)$$

It is easy to prove that $[T]$ from (18) does indeed diagonalize the matrix product in (12). First, recall that

$$[T]^{-1} = [S]^{-1}[C'_{phase}]^{-1}$$

Premultiplying $[j\omega C'_{phase}][Z'_{phase}]$ with $[T]^{-1}$ and post-multiplying with $[T]$ is seen to be equal to $[\Lambda]$ when compared against (15):

$$[S]^{-1}\underbrace{[C'_{phase}]^{-1}[j\omega C'_{phase}]}_{=j\omega}[Z'_{phase}][C'_{phase}][S] = [\Lambda]$$

The eigenvalues have a physical meaning. By taking any one mode from eq. (13), say

$$\frac{d^2 V_{mode\ i}}{dx^2} = \lambda_i V_{mode\ i}$$

and comparing it with the corresponding equation of a single phase line

---

* For this reason, it is generally not just a coordinate (or similarity) transformation.

which is $\frac{d^2V}{dx^2} = \gamma^2 \cdot V$

$$\text{with } \gamma^2 = (R' + j\omega L')j\omega C'$$

we see that the propagation constant γ_i of the independent mode must be

$$\gamma_i = \sqrt{\lambda_i} \tag{20}$$

with $\mathrm{Re}\{\gamma_i\}$ = attenuation constant, e.g., in nepers/mile
$\mathrm{Im}\{\gamma_i\}$ = phase constant, e.g., in radians/mile

The surge impedance of a mode is not uniquely defined because the matrices [S] and [T] are not uniquely defined if they are not normalized. Let us recall that the surge impedance of a single phase line is defined by

$$Z_{surge} = \sqrt{\frac{R' + j\omega L'}{j\omega C'}}$$

To find the corresponding expression for the modes, the series impedance matrix $[Z'_{mode}] = [R'_{mode}] + j\omega [L'_{mode}]$ and capacitance matrix $[C'_{mode}]$ must first be found in modal quantities. This is done by transforming (9) and (10) into the modal domain:

$$-\left[\frac{dV_{mode}}{dx}\right] = \underbrace{[S]^{-1}[Z'_{phase}][T]_{normalized}}_{[Z'_{mode}]} \cdot [I_{mode}]$$

$$\text{and} \quad -\left[\frac{dI_{mode}}{dx}\right] = \underbrace{[T]^{-1}_{normalized}[j\omega C'_{phase}][S]}_{[j\omega C'_{mode}]} \cdot [V_{mode}]$$

Both matrices are diagonal, which can be seen by inserting $[T]_{normalized}$ from (19) and (18):

$$[Z'_{mode}] = \frac{1}{j\omega}[\Lambda][D]^{-1} = \frac{1}{j\omega}\begin{bmatrix} \frac{\lambda_1}{d_1} & & & & \\ & \frac{\lambda_2}{d_2} & & & \\ & & \frac{\lambda_3}{d_3} & & \\ & & & \ddots & \\ & & & & \frac{\lambda_M}{d_M} \end{bmatrix}$$

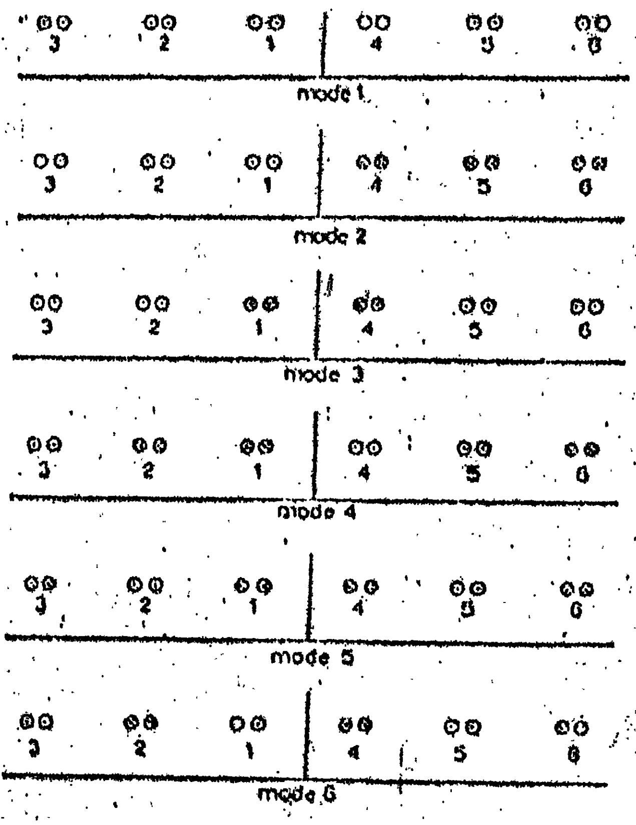
$$\text{and} \quad [j\omega C'_{mode}] = j\omega [D] = j\omega \begin{bmatrix} d_1 & & & & \\ & d_2 & & & \\ & & d_3 & & \\ & & & \ddots & \\ & & & & d_M \end{bmatrix}$$

Therefore we get $$(Z_{surge})_{mode\text{-}i} = \sqrt{\frac{\lambda_i}{-\omega^2 d_i^2}} = \frac{1}{\omega d_i}\sqrt{-\lambda_i} \tag{21}$$

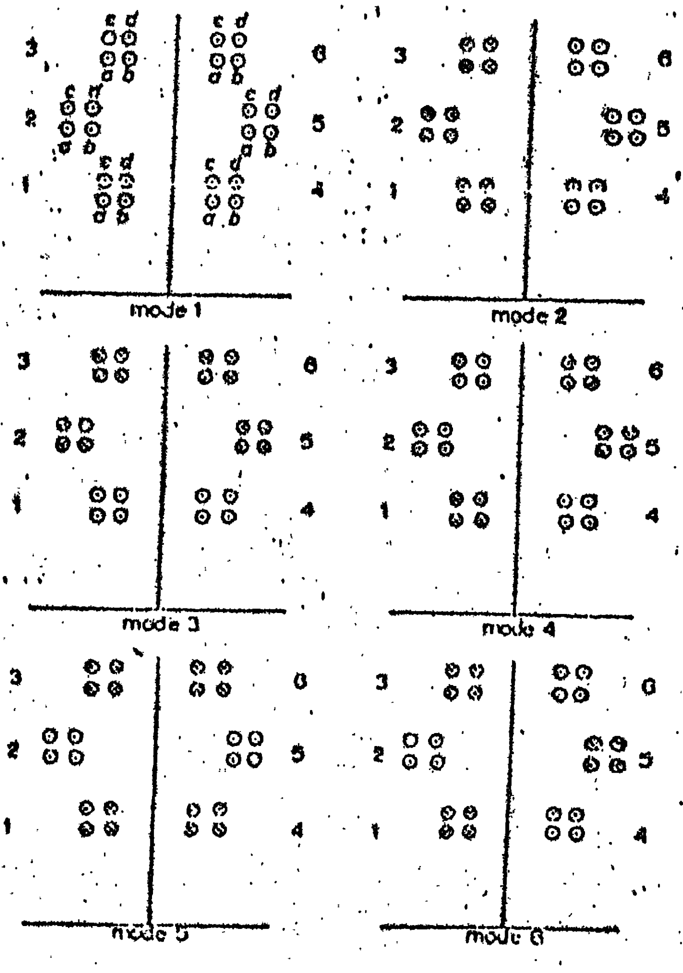
For unnormalized [T] , set all $d_i = 1$ in eq. (21).

Modal analysis has been used to study power line carrier problems [10, 1 , 17] as well as radio noise interference [18,19] . It is interesting to note that the modal distribution in single circuits with horizontal configuration is practically identical with $\alpha, \beta, 0$- components [20] . Fig. 2 taken from [19] gives an interesting picture of the distribution of mode currents in double circuit lines at 1MHz (each mode is independent of the others). Note that the modal transformation has only been defined for one specific frequency, in general a different transformation must be used if the frequency is changed.

This leads to difficulties in studying transient phenomena containing many frequencies. In time domain solutions one is almost forced to assume that the transformation matrix does not change over a certain frequency range. In frequency domain solutions it is always possible, though costly, to find a new transformation matrix at each frequency.



Distribution of mode currents in conductors of double-circuit horizontal line
$f = 1$ MHz
$\rho = 100\ \Omega$m



Distribution of mode currents in conductors of double-circuit vertical line
$f = 1$ MHz
$\rho = 100\ \Omega$m

FIG. 2. Distribution of mode currents

5. SYMMETRICAL AND OTHER COMPONENTS FOR TRANSPOSED AND BALANCED LINES

Power lines are transposed to equalize the series impedance and shunt capacitance among the phases to avoid unbalances in voltages and/or currents. Transposed lines can be studied much easier with symmetrical components, because the 3 coupled equations in the phase domain,

$$-\begin{bmatrix} \frac{dV_A}{dx} \\ \frac{dV_B}{dx} \\ \frac{dV_C}{dx} \end{bmatrix} = \begin{bmatrix} Z'_{AA} & Z'_{AB} & Z'_{AC} \\ Z'_{BA} & Z'_{BB} & Z'_{BC} \\ Z'_{CA} & Z'_{CB} & Z'_{CC} \end{bmatrix} \cdot \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

become 3 decoupled equations in the domain of symmetrical components,

$$-\frac{dV_{zero}}{dx} = Z'_{zero} \cdot I_{zero}$$

$$-\frac{dV_{pos}}{dx} = Z'_{pos} \cdot I_{pos}$$

$$-\frac{dV_{neg}}{dx} = Z'_{neg} \cdot I_{neg}$$

This decoupling effect is the primary reason for using symmetrical components instead of phase quantities. It should be remembered, however, that this simplification is only true for transposed lines. Therefore, it would be foolish to study untransposed lines with symmetrical components. Instead, coupled equations in the phase domain ormodal transformations as described in section 4 should be used for untransposed lines.

Theoretically, the line would have to be continuously transposed to get decoupled equations in the domain of symmetrical components. Of course, such a line cannot be built.! But the decoupling effect is still realized with sufficient accuracy for lines with practical transposition, as long as

(a) the transposition sections have approximately equal length, and

(b) the length of a complete transposition cycle (3 sections for a single circuit) is much shorter than the wave length of the frequencies involved in the study.

Because of the second assumption symmetrical components are of little use in carrier problems. If assumption (b) is true, then it is permissible to equalize the series impedances by themselves and to equalize the shunt capacitances by themselves. The process will only be shown for the series impedances because it is analogous for the shunt capacitances.

5.1 Symmetrical components for three-phase single circuits

For a single three-phase circuit there is only one way of transposition as shown in Fig. 3. Each conductor occupies all 3 possible locations i,k,m within a complete transposition cycle of 3 sections I, II and III. The voltage drop per unit length is the sum of the voltage drops in the 3 sections.*)

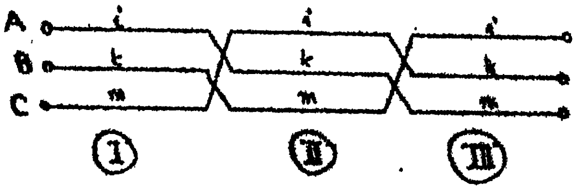


Fig. 3. Transposition for single circuit.

$$\begin{bmatrix} \Delta V_A \\ \Delta V_B \\ \Delta V_C \end{bmatrix} = \begin{bmatrix} \Delta V_{i-I} \\ \Delta V_{k-I} \\ \Delta V_{m-I} \end{bmatrix} + \begin{bmatrix} \Delta V_{k-II} \\ \Delta V_{m-II} \\ \Delta V_{i-II} \end{bmatrix} + \begin{bmatrix} \Delta V_{m-III} \\ \Delta V_{i-III} \\ \Delta V_{k-III} \end{bmatrix}.$$

For each section the series impedance is

$$\frac{1}{3}\begin{bmatrix} Z'_{ii} & Z'_{ik} & Z'_{im} \\ Z'_{ki} & Z'_{kk} & Z'_{km} \\ Z'_{mi} & Z'_{mk} & Z'_{mm} \end{bmatrix}.$$

---

*) ΔV_A is used for $-\frac{dV_A}{dx}$

If we define
$$\begin{bmatrix}\Delta V_A\\ \Delta V_B\\ \Delta V_C\end{bmatrix} = \begin{bmatrix} Z'_{phase} \end{bmatrix} \cdot \begin{bmatrix} I_A\\ I_B\\ I_C\end{bmatrix} \qquad (22a)$$

than we see that
$$\left[Z'_{phase}\right] = \frac{1}{3}\left\{\begin{bmatrix} Z'_{ii} & Z'_{ik} & Z'_{im}\\ Z'_{ki} & Z'_{kk} & Z'_{km}\\ Z'_{mi} & Z'_{mk} & Z'_{mm}\end{bmatrix} + \begin{bmatrix} Z'_{kk} & Z'_{km} & Z'_{ki}\\ Z'_{mk} & Z'_{mm} & Z'_{mi}\\ Z'_{ik} & Z'_{im} & Z'_{ii}\end{bmatrix} + \begin{bmatrix} Z'_{mm} & Z'_{mi} & Z'_{mk}\\ Z'_{im} & Z'_{ii} & Z'_{ik}\\ Z'_{km} & Z'_{ki} & Z'_{kk}\end{bmatrix}\right\} \qquad (22b)$$

Remembering that $Z'_{ik} = Z'_{ki}$ etc. in (22) and introducing average values for self and mutual impedances,
$$Z'_s = \frac{1}{3}\left(Z'_{ii} + Z'_{kk} + Z'_{mm}\right)$$
$$Z'_m = \frac{1}{3}\left(Z'_{ik} + Z'_{km} + Z'_{mi}\right) \qquad (23)$$

one gets
$$\left[Z'_{phase}\right] = \begin{bmatrix} Z'_s & Z'_m & Z'_m\\ Z'_m & Z'_s & Z'_m\\ Z'_m & Z'_m & Z'_s\end{bmatrix}$$

where all diagonal elements ("self") and off-diagonal elements ("mutual") are equal among themselves.*This is not too surprising because transposition is used in the first place to equalize the impedances.

Symmetrical components are obtained through the linear transformations (identical for voltages and currents)
$$\begin{bmatrix} I_{zero}\\ I_{pos.}\\ I_{neg.}\end{bmatrix} = \underbrace{\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}}_{[S]^{-1}} \cdot \begin{bmatrix} I_A\\ I_B\\ I_C\end{bmatrix} \qquad (24a)$$

and
$$\begin{bmatrix} I_A\\ I_B\\ I_C\end{bmatrix} = \underbrace{\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 1 & 1\\ 1 & a^2 & a\\ 1 & a & a^2\end{bmatrix}}_{\equiv [S]} \cdot \begin{bmatrix} I_{zero}\\ I_{pos.}\\ I_{neg.}\end{bmatrix} \qquad (24b)$$

---

* Matrices with these properties will be called "balanced".

with $a = e^{j120°}$ The sequence quantities in (24a) and (24b) are normalized. Often, unnormalized quantities are used; then the factor in (24a) is $1/3$ instead of $1/\sqrt{3}$ and in (24b) it is 1 instead of $1/\sqrt{3}$.* With these transformations, eq. (22a) is transformed into

$$\begin{bmatrix} \Delta V_{zero} \\ \Delta V_{pos.} \\ \Delta V_{neg.} \end{bmatrix} = \underbrace{[S]^{-1}[Z'_{phase}][S]}_{[Z'_{symm}]} \cdot \begin{bmatrix} I_{zero} \\ I_{pos} \\ I_{neg.} \end{bmatrix} \qquad (25a)$$

with

$$[Z'_{symm}] = \begin{bmatrix} Z'_s + 2Z'_m & 0 & 0 \\ 0 & Z'_s - Z'_m & 0 \\ 0 & 0 & Z'_s - Z'_m \end{bmatrix} \qquad (25b)$$

The diagonal form of the matrix in eq. (25b) proves that the equations do indeed become decoupled.

Positive and negative sequence quantities are identical. The zero and positive sequence series resistance and inductance are a function of the frequency as shown in Fig. 4. All capacitance matrices are independent of frequency.

Practical computation of sequence quantities: It is not necessary to carry out the averaging process of eq. (22b). Instead, the series impedance matrix for the untransposed line can be transformed directly, yielding

$$[Z'^{\,untransposed}_{symm}] = [S]^{-1} \begin{bmatrix} Z'_{ii} & Z'_{ik} & Z'_{im} \\ Z'_{ki} & Z'_{kk} & Z'_{km} \\ Z'_{mi} & Z'_{mk} & Z'_{mm} \end{bmatrix} [S] = \begin{bmatrix} \boxed{\begin{matrix} Z'_s + 2Z'_m \\ (Z'_{zero}) \end{matrix}} & Z'_{zero,pos.} & Z'_{zero,neg.} \\ Z'_{pos.,zero} & \boxed{\begin{matrix} Z'_s - Z'_m \\ (Z'_{pos.}) \end{matrix}} & Z'_{pos.,neg.} \\ Z'_{neg.,zero} & Z'_{neg.,pos} & \boxed{\begin{matrix} Z'_s - Z'_m \\ (Z'_{neg.}) \end{matrix}} \end{bmatrix}$$

This is the matrix which is produced by the line constants program. If the line is transposed, simply ignore the coupling terms.

The diagonal elements are the desired sequence quantities. The off-diagonal elements are not zero anymore. Their values are useful for untransposed lines because they show the coupling between sequence quantities. Often, unbalance factors are derived from them [22], such as

$$M_o = \left| \frac{Z'_{zero,\,pos.}}{Z'_{zero}} \right| \cdot 100$$

which is the percent coupling from zero sequence to positive sequence

*Normalization has no influence on the sequence impedance, because the factors always cancel out in the product $[S]^{-1}[Z_{phase}]*[S]$. However it does influence the sealing of sequence currents and voltages as expressed

608

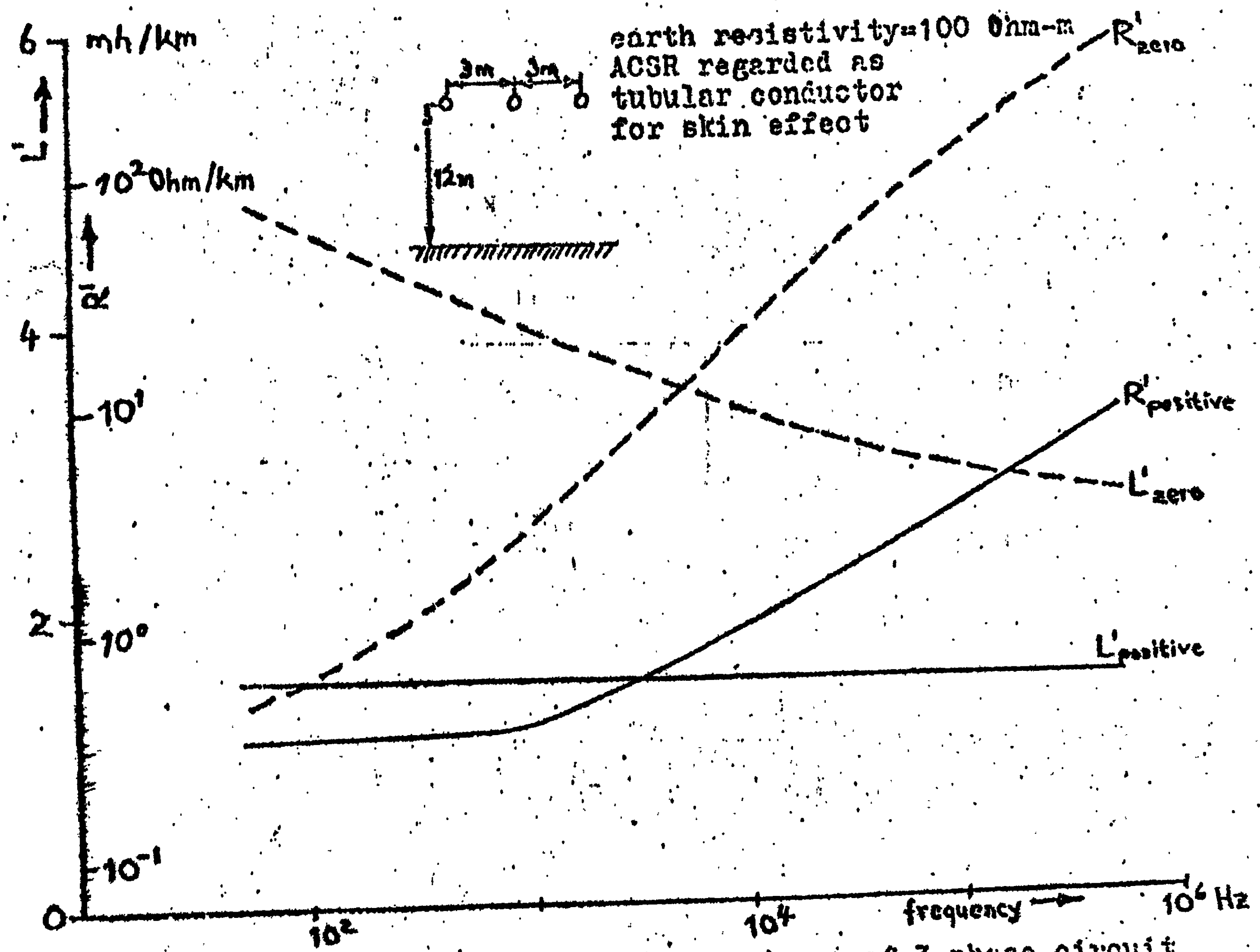


Fig.4. Positive and zero sequence impedance of 3-phase circuit

5.2 Symmetrical components for three-phase double and more circuits

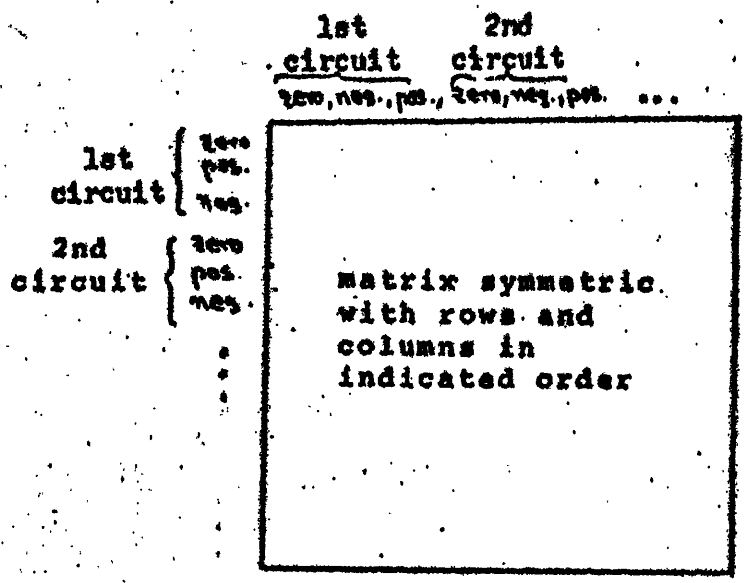
The ideas of transposition can be extended to double circuits (2 three-phase circuits on one tower). However, there will always be coupling between the zero sequences of the two circuits. Appendix 5 gives a summary of the pertinent results for the double circuit line.

In general, the transformation for K three-phase circuits has the form

$$\left[Z'^{\,\text{untransposed}}_{\text{symm}}\right] = \underbrace{\begin{bmatrix} [S]^{-1} & & & & \\ & [S]^{-1} & & & \\ & & [S]^{-1} & & \\ & & & \ddots & \\ & & & & [S]^{-1} \end{bmatrix}}_{\text{block-diagonal}} \underbrace{\begin{bmatrix} & & \\ & Z'_{\text{phase}} & \\ & & \end{bmatrix}}_{(3K)\times(3K)\text{ matrix}} \underbrace{\begin{bmatrix} [S] & & & & \\ & [S] & & & \\ & & [S] & & \\ & & & \ddots & \\ & & & & [S] \end{bmatrix}}_{\text{block-diagonal}} \qquad (26)$$

Trick for retaining symmetry in symmetrical component matrices

Computer programs usually take advantage of symmetry in the original matrices for all physical conductors and in the reduced matrices for the equivalent phase conductors by computing and storing elements in and below the diagonal only. This cannot be done directly for $[Z'^{\text{untransposed}}_{\text{symm}}]$ in (26) because the transformation destroys the symmetry. However, Shipley proposed a scheme of exchanging certain columns in $[Z'^{\text{untransposed}}_{\text{symm}}]$ which preserves the symmetry [1,2]. For K three-phase circuits, the result will be in the order


1st circuit
2nd circuit
zero, neg., pos., zero, neg., pos. ...
1st circuit
zero
pos.
neg.
2nd circuit
zero
pos.
neg.
matrix symmetric with rows and columns in indicated order

Obviously, the equality $Z'_{\text{zero,neg.}} = Z'_{\text{pos.,zero}}$ etc.

must be true.

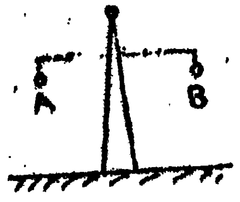
5.3 Karrenbauer's transformation

See section 4.1 of SUPPLEMENT to paper "Digital computer solution of electromagnetic transients in single and multiphase networks" by H.W. Dommel, dated April 1970.

5.4 Symmetrical components for two-pole HVDC line

The idea of symmetrical components can be generalized to M phases. Therefore, it can also be used for two-pole HVDC lines. There are some arguments, however, whether it is wise to use the words "symmetrical components" and "zero and positive sequence". Indeed, zero sequence and positive sequence of a two-pole symmetric line are identical with the ground mode and metallic mode of Karrenbauer's transformation.

There is no need to transpose a symmetric two-pole line with conductors at equal height, because the impedances are already equal, with



$$[Z'_{phase}] = \begin{bmatrix} Z'_s & Z'_m \\ Z'_m & Z'_s \end{bmatrix}$$

(assuming identical conductors or bundle conductors in A and B at equal height, and symmetrically placed ground wires, if any)

The transformation (identical for voltages and currents) is

$$\begin{bmatrix} I_{zero} \\ I_{pos.} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} I_A \\ I_B \end{bmatrix}$$

and

$$\begin{bmatrix} I_A \\ I_B \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} I_{zero} \\ I_{pos.} \end{bmatrix}$$

and the associated matrix in symmetrical components

$$[Z'_{symm}] = \begin{bmatrix} Z'_s + Z'_m & 0 \\ 0 & Z'_s - Z'_m \end{bmatrix}$$

*For unnormalized sequence quantities, the factor in the first equation would be $\frac{1}{2}$ instead of $\frac{1}{\sqrt{2}}$ and in the second equation 1 instead of $\frac{1}{\sqrt{2}}$.

6. EQUIVALENT MULTI-π-CIRCUIT FOR UNTRANSPOSED LINES

A multiphase line can be represented by an equivalent multi-π-circuit, which correctly describes the steady-state conditions at its terminals for a specific frequency and length. This is the generalization of the well-known equivalent π for the single-phase line. Note that such equivalents represent the line only for steady-state conditions (frequency and length fixed); they cannot be used for transient phenomena and give no information between the terminals along the line.

The equivalent multi-π is characterized by a transfer admittance matrix [$Y_{transfer}$] from terminal 1 to 2 and a shunt admittance matrix [Y_{shunt}] at both terminals (see Fig.5,p.21). Their meaning is expressed in the formulas

$$\left[\begin{array}{c|c} [Y_{transfer}] + [Y_{shunt}] & -[Y_{transfer}] \\ \hline -[Y_{transfer}] & [Y_{transfer}] + [Y_{shunt}] \end{array}\right] \left[\begin{array}{c} [V_1] \\ \hline [V_2] \end{array}\right] = \left[\begin{array}{c} [I_1] \\ \hline [I_2] \end{array}\right] \qquad (27)$$

where [V_1], [V_2], [I_1], [I_2] are the voltage and current vectors at both terminals. If the line has M phases, then [$Y_{transfer}$], [Y_{shunt}] are M x M matrices and (27) is a system of 2M equations.

Transposed and singl -phase lines

It is well known how to compute $Y_{transfer}$ and Y_{shunt} for the single-phase line,

$$Y_{transfer} = \frac{1}{B} \text{ and } Y_{shunt} = (A-1) \cdot Y_{transfer} \qquad (28)$$

$$\text{with } A = \cosh\left(s\sqrt{z'y'}\right)$$

$$B = \sqrt{\frac{z'}{y'}} \cdot \sinh\left(s\sqrt{z'y'}\right)$$

s = length of line
z' = series impedance per-unit length
y' = shunt admittance per-unit length

use these equations for transposed lines in each sequence

Fig. 6 shows $Z_{transfer} = 1/Y_{transfer}$ and Y_{shunt} for a single-phase line as a function of length. If the line-length is short, compared to the wave length, then

$$\left.\begin{aligned} Z_{transfer} &= 1/Y_{transfer} \approx s.z' \\ Y_{shunt} &\approx s.y' \end{aligned}\right\} \text{ for } s \ll \lambda \qquad (29)$$

This is sometimes called the nominal π in contrast to the exact equivalent π.

For transposed lines each sequence is computed independently with eq. (28). The solution is more difficult for untransposed lines, in that case, the scalar equations (28) can be generalized for the multiphase lin by using eigenvalues [4]. A different approach is used in BPA's program, which was indicated in a discussion to ref. 4 by W. F. Tinney. First choose an incremental length Δs which is short enough to justify the us of equation (29).

The respective equivalent multi-π for length Δs then has

$$\left.\begin{aligned} [Y_{transfer}] &= \frac{1}{\Delta s} \cdot [z']^{-1} \\ [Y_{shunt}] &= \frac{\Delta s}{2} \cdot [y'] \end{aligned}\right. \quad \text{with} \begin{cases} [z'] = \text{series impedance matrix p.u. length} \\ [y'] = \text{shunt admittance matrix p.u. length} \end{cases} \qquad (29b)$$

If two such equivalents are now connected in series (Fig. 7), one gets a new equivalent for the doubled length $2 \cdot \Delta s$ after eliminating the passive "inner" nodes (3) in the system of 3N nodal equations. An efficient elimination scheme is explained in appendix 6. This doubling of the length by series connection of the latest equivalents will finally lead to an equivalent for the desired length s, via equivalents for Δs, $2\Delta s$, $4\Delta s$, $8\Delta s$, ... (Δs is chosen such that $2^k \cdot \Delta s = s$ with k = positive integer, in order to arrive exactly at the length s). Two bounds must be taken into account in the choice of Δs; on one hand it should be small enough to justify the use of eq.(29), on the other hand it should not be so small as to cause serious round-off errors and an excessive number of doubling procedures. Appendix 7 shows how Δs is chosen by the computer. With this choice, the values for the single-phase line of Fig. 6 compare at 800 miles with the exact values as follows (Δs was 12.5 miles):

	$Y_{transfer}$ in mho	Y_{shunt} in mho
through successive doubling	0.16800-j2.5881	0.13546+j2.8073
exact	0.16800-j2.5883	0.13548+j2.8074

For a three-phase line of 200 miles, used in ref. 4, the results had a maximum relative error in magnitude of $1 \cdot 10^{-4}$ and a maximum phase error of 0.03° in the transfer impedance and shunt admittance elements.

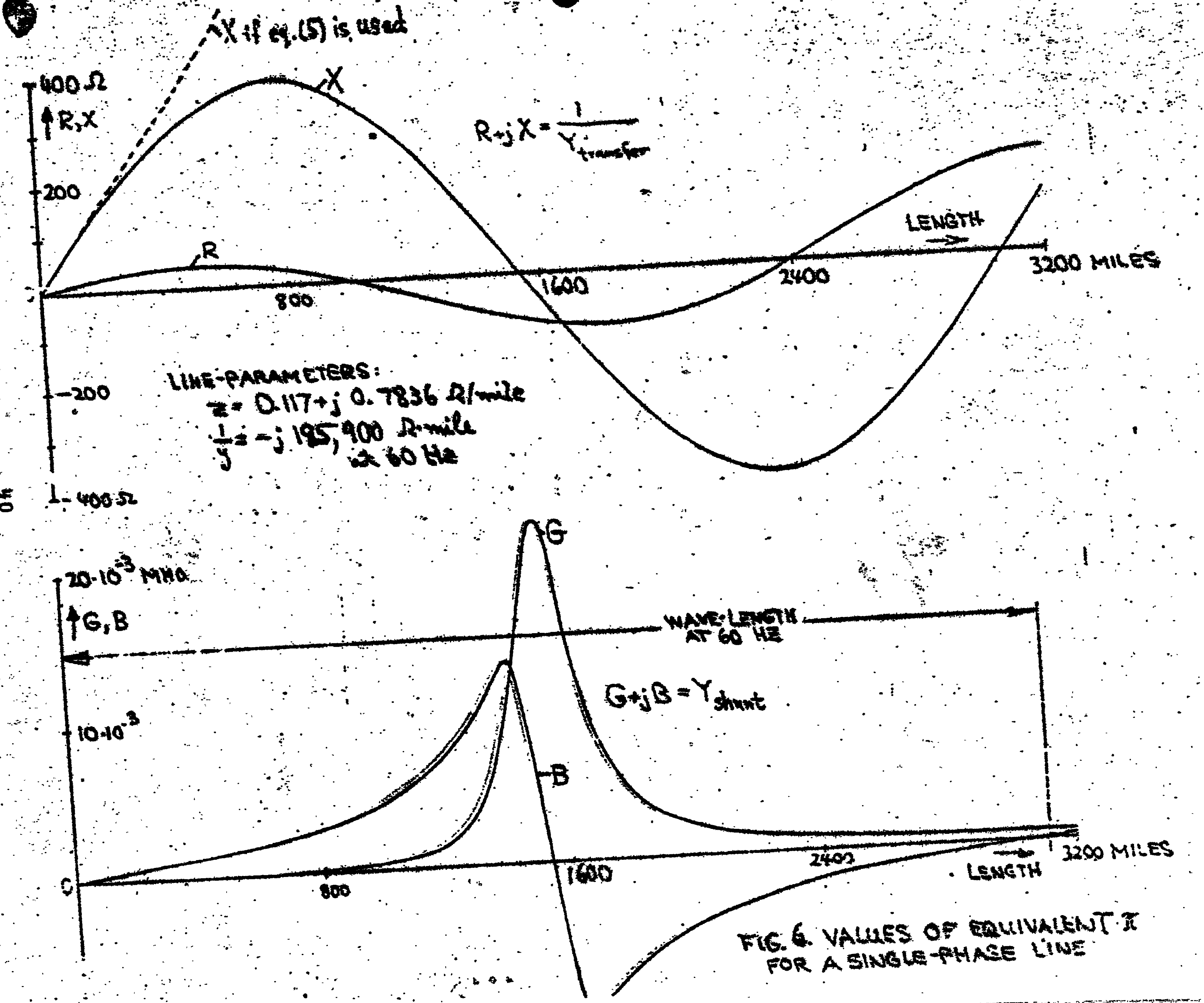


FIG. 6. VALUES OF EQUIVALENT π FOR A SINGLE-PHASE LINE

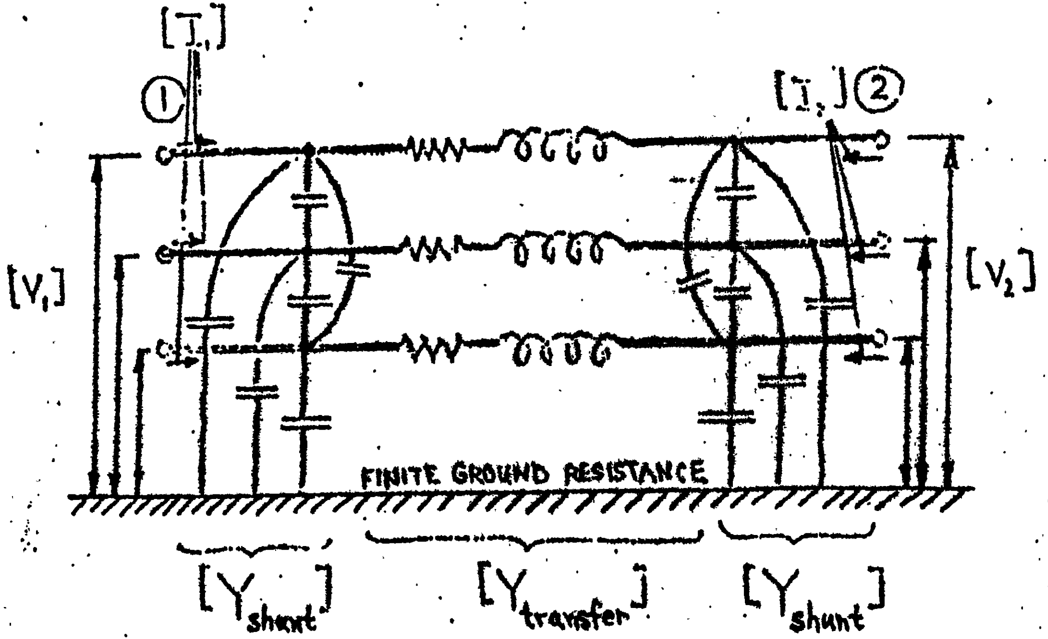


FIG. 5. EQUIVALENT MULTI-π CIRCUIT

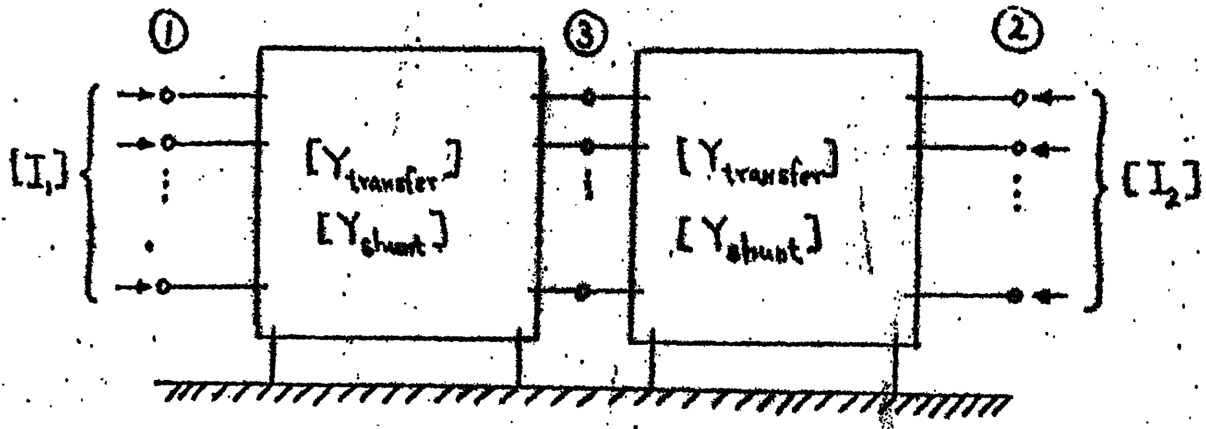
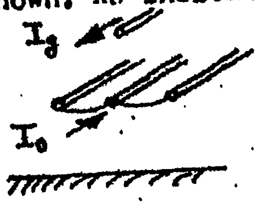


FIG. 7. SERIES CONNECTION OF 2 IDENTICAL EQUIVALENTS

7. SCREENING MATRIX

In interference studies the current in the ground wires must also be known. As indicated in the sketch, a zero sequence current in the phases returns partly through the ground wire. This ground wire current cancels part of the voltage induced in neighboring communication lines by the zero sequence current, thus acting as a "screen" for magnetic induction. Since the line constants normally used have the ground wires eliminated, it is necessary to recover the ground current. For the case indicated in the sketch with all 3 phases bundled to simulate zero sequence operation, one would have a system of 2 equations



$$\begin{bmatrix} -\frac{dV_0}{dx} \\ 0 \end{bmatrix} = \begin{bmatrix} Z'_{00} & Z'_{0g} \\ Z'_{g0} & Z'_{gg} \end{bmatrix} \begin{bmatrix} I_0 \\ I_g \end{bmatrix}.$$

The second equation permits the recovery of the ground current I_g :

$$I_g = -\frac{Z'_{g0}}{Z'_{gg}} I_0 \quad , \text{ where } -\frac{Z'_{g0}}{Z'_{gg}}$$ is called the screening factor. The impedances are:

Z'_{gg} = self impedance of ground wire

Z'_{g0} = mutual impedance between zero sequence bundle of phase conductors and ground wire.

The idea can easily be generalized for the multiphase line. Let

F = subset of all phases (after bundling has been carried out)
G = subset of all ground wires.

Th n

$$\begin{bmatrix} -\left[\frac{dV_F}{dx}\right] \\ 0 \end{bmatrix} = \begin{bmatrix} [Z'_{FF}] & [Z'_{FG}] \\ [Z'_{GF}] & [Z'_{GG}] \end{bmatrix} \begin{bmatrix} [I_F] \\ [I_G] \end{bmatrix}$$

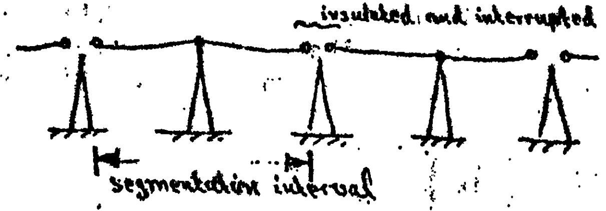
From this, the recovery of currents in the ground wires is seen to be

$$[I_G] = \underbrace{-[Z_{GG}]^{-1}[Z_{GF}]}_{\text{Screening matrix}} [I_F]$$

The screening matrix is the transposed of the distribution factor matrix explained in appendix 4. As indicated in the flow chart for REDUCT in appendix 4, the transposed distribution factor matrix and, therefore, the screening matrix, are directly obtained as a by-product of the reduction process.

Fig. 8 shows the phase currents in the 2 poles of an HVDC line for the sixth harmonic (360 Hz) as a function of line distance. The currents in the two ground wires (LT.GRD. = left ground wire, RT.GRD. = right ground wire) which are also plotted were recovered with the screening matrix mentioned above [7].

8. SEGMENTED GROUND WIRES



Segmented ground wires are interrupted and insulated at certain intervals to prevent the flow of circulating currents. In effect, they act as an electrostatic shield. Segmented ground wires will not carry any noticeable current as long as the wave length of the particular frequency is much larger than the length of the segmentation interval. This is true at power frequency but is not true at higher frequencies associated with lightning surges. For switching surges it may or may not be true.

The nature of the segmentation is taken into account by ignoring the ground wires in the computation of the series impedance matrix but considering them in the computation of the shunt capacitance matrix.

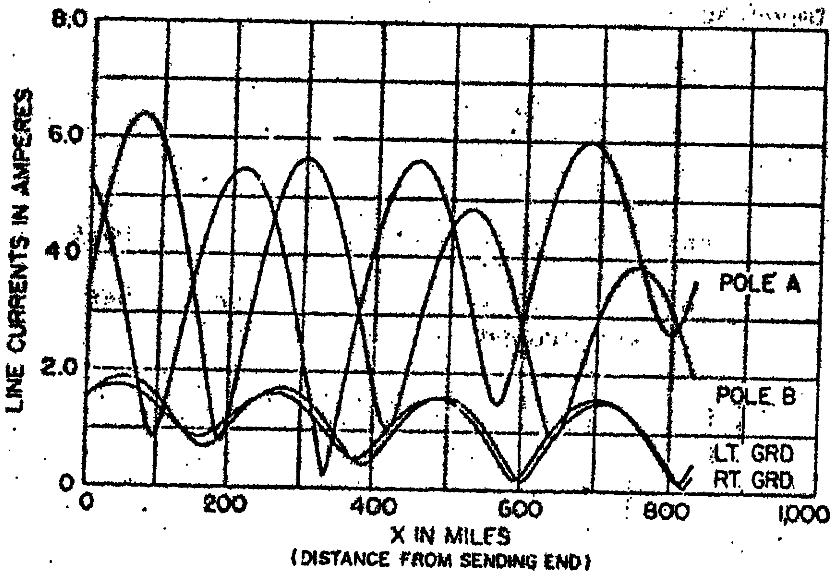


Fig. 8. Currents of sixth harmonic in HVDC line

Classical textbooks always equate the positive sequence resistance with the conductor resistance (for bundle conductors

$$R = \frac{\text{resistance for individual conductor}}{\text{number of conductors in bundle}},$$

possibly corrected for conductor skin effect. The values obtained with the exact formulas may differ slightly for two reasons:

(a) The ground return influences the positive sequence impedance slightly which is not borne out by classical formulas. The influence is usually very small at 60 Hz but may become noticeable at higher frequencies.

(b) The presence of ground wires may have a noticeable effect on the positive sequence impedance. A particular case at 60 Hz gave

$$R_{conductor} = 0.0657 \ \Omega/\text{mile}$$

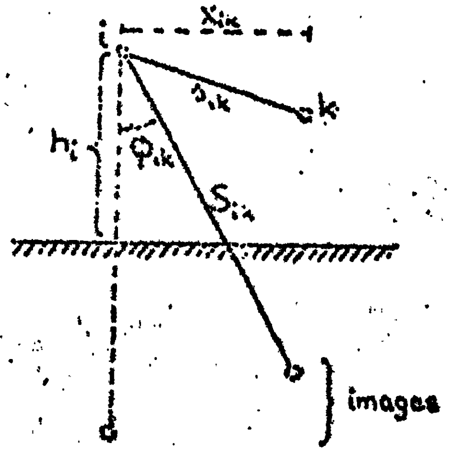
$$R_{positive} = 0.0703 \ \Omega/\text{mile, which is}$$

6-1/2% higher

This difference is primarily caused by the presence of a ground wire. Even under symmetric (positive sequence) operation the voltages induced in the ground wire by the symmetric currents in the 3 phases will not cancel entirely because the distances from the phase conductors to the ground wire and, therefore, the mutual impedances, are usually not all equal. The remaining induced voltage will cause a circulating current (return through ground); the associated losses are proportional to the positive sequence current and are accounted for by an increase in the positive sequence resistance. This effect will not show up with segmentation of ground wires. As a matter of fact, this is the reason for using segmentation.

APPENDICES

Appendix 1. Line parameters



a) Series impedance. Carson's formula[12] is used for calculating the impedance matrix[Z']. It is based on the assumptions that the conductors are long enough, so that end effects may be neglected, and that the earth has uniform conductivity and is bounded by a flat plane with infinite extent, to which the conductors are parallel. As average height above ground the value "height at midspan + 1/3 of sag" is usually taken. The spacing between conductors is assumed large enough to neglect the proximity effect. The elements of[Z']are for the self impedance

$$Z'_{ii} = (R'_{ii} + \Delta R'_{ii}) + j\,(2\omega\cdot 10^{-4} \ln \frac{2h_i}{GMR_i} + \Delta X'_{ii}) \quad \text{in ohm/km} \qquad (30)$$

and for the mutual impedance

$$Z'_{ik} = Z'_{ki} = \Delta R'_{ik} + j\,(2\omega\cdot 10^{-4} \ln \frac{S_{ik}}{s_{ik}} + \Delta X'_{ik}) \quad \text{in ohm/km} \qquad (31)$$

with R'_{ii} = resistance of conductor i (for skin effect see app.2) in ohm/km

h_i = height above ground of conductor i
S_{ik} = distance between conductor i and image of conductor k
s_{ik} = distance between conductors i and k
GMR_i = geometric mean radius of conductor i (for skin effect see app.2)
(in the same units, e.g., in m)

ω = $2\pi f$ with f=frequency in cps.

The corrections $\Delta R'$ and $\Delta X'$ account for the earth return effect and are functions of the angle ϕ ($\phi = 0$ for self impedance, $\phi = \phi_{ik}$ for mutual impedance) and the parameter a:

$$a = k\cdot S\cdot\sqrt{\frac{f}{\varrho}}\ , \qquad k = 4\pi\sqrt{5}\cdot 10^{-4} \qquad (32)$$

with $S = \begin{cases} 2h_i & \text{for self impedance in m} \\ S_{ik} & \text{for mutual impedance in m} \end{cases}$

ϱ = earth resistivity in ohm-m.

$\Delta R'$ and $\Delta X'$ become zero for $a \to \infty$ (very high frequency or very low earth resistivity). Carson gives an infinite integral for $\Delta R'$ and $\Delta X'$, which he developed into the following infinite series for $a \leq 5$ (rearranged for computer purposes):

$$\begin{array}{l|l}
\Delta R' = 4\omega\cdot 10^{-4}\Big\{\frac{\pi}{8} & \Delta X' = 4\omega\cdot 10^{-4}\Big\{\frac{1}{2}(0.6159315-\ln a) \\
\quad -b_1 a\cdot\cos\phi & \quad +b_1 a\cdot\cos\phi \\
\quad +b_2\left[(c_2-\ln a)a^2\cos 2\phi+\phi a^2\sin 2\phi\right] & \quad -d_2 a^2\cos 2\phi \\
\quad +b_3 a^3\cos 3\phi & \quad +b_3 a^3\cos 3\phi \\
\quad -d_4 a^4\cos 4\phi & \quad -b_4\left[(c_4-\ln a)a^4\cos 4\phi+\phi a^4\sin 4\phi\right] \\
\quad -b_5 a^5\cos 5\phi & \quad +b_5 a^5\cos 5\phi \\
\quad +b_6\left[(c_6-\ln a)a^6\cos 6\phi+\phi a^6\sin 6\phi\right] & \quad -d_6 a^6\cos 6\phi \\
\quad +b_7 a^7\cos 7\phi & \quad +b_7 a^7\cos 7\phi \\
\quad -d_2 a^8\cos 8\phi & \quad -b_8\left[(c_8-\ln a)a^8\cos 8\phi+\phi a^8\sin 8\phi\right] \\
\quad -\ldots\Big\} & \quad +\ldots\Big\}
\end{array} \qquad (33)$$

Each 4 successive terms form a repetitive pattern. The coefficients b_i, c_i and d_i are constants, which can be precalculated and stored in lists. They are obtained from the recursive formulas:

$$b_i = b_{i-2}\,\frac{\text{sign}}{i(i+2)} \quad \text{with the starting value} \quad \begin{cases} b_1=\frac{\sqrt{2}}{6} & \text{for odd subscripts} \\ b_2=\frac{1}{16} & \text{for even subscripts} \end{cases} \qquad (34)$$

$$c_i = c_{i-2} + \frac{1}{i} + \frac{1}{i+2} \quad \text{with the starting value } c_2 = 1.3659315$$

$$d_i = \frac{\pi}{4}\cdot b_i$$

with sign = ±1 changing after each 4 successive terms (sign=+1 for i=1,2,3,4; sign=−1 for i=5,6,7,8 etc.).
For a>5 the following finite series is best used[13]*:

$$\Delta R' = \left(\frac{\cos\phi}{a} - \frac{\sqrt{2}\cos 2\phi}{a^2} + \frac{\cos 3\phi}{a^3} + \frac{3\cos 5\phi}{a^5} - \frac{45\cos 7\phi}{a^7}\right)\cdot\frac{4\omega\cdot 10^{-4}}{\sqrt{2}} \qquad (35)$$

$$\Delta X' = \left(\frac{\cos\phi}{a} - \frac{\cos 3\phi}{a^3} + \frac{3\cos 5\phi}{a^5} + \frac{45\cos 7\phi}{a^7}\right)\cdot\frac{4\omega\cdot 10^{-4}}{\sqrt{2}}$$

The trigonometric functions are calculated directly from the geometry, for conductors i and k:

$$\cos\phi_{ik} = \frac{h_i + h_k}{S_{ik}} \quad \text{and} \quad \sin\phi_{ik} = \frac{x_{ik}}{S_{ik}}$$

and for higher terms in the series from the recursive formulas

$$a^i\cos i\phi = \left[a^{i-1}\cos(i-1)\phi\cdot\cos\phi - a^{i-1}\sin(i-1)\phi\cdot\sin\phi\right]\cdot a \qquad (36)$$

$$a^i\sin i\phi = \left[a^{i-1}\cos(i-1)\phi\cdot\sin\phi + a^{i-1}\sin(i-1)\phi\cdot\cos\phi\right]\cdot a$$

For power circuits at power frequency only few terms in the series of (33) are necessary. The formulas in most textbooks are based on the first few terms. However at higher frequencies and wider spacings – e.g., in interference calculations – the parameter a becomes larger and more and more terms must be taken into

---

*This is obtained from an asymptotic expansion of Carson's formula (derivable by repeated partial integrations) and is already shown in Carson's original paper [17]. Butterworth carries it further to include one more term.

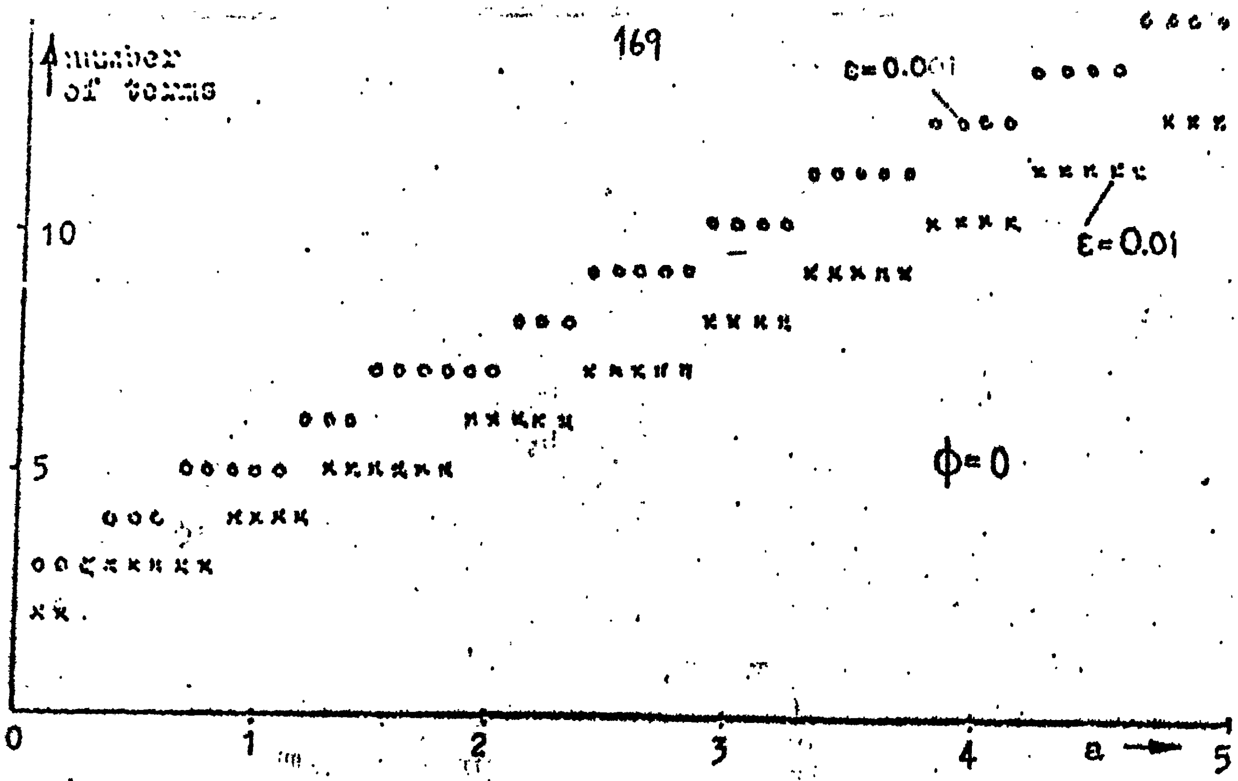


Fig. 9. Number of terms in series of (33) to get an accuracy of ε = 0.01 and 0.001

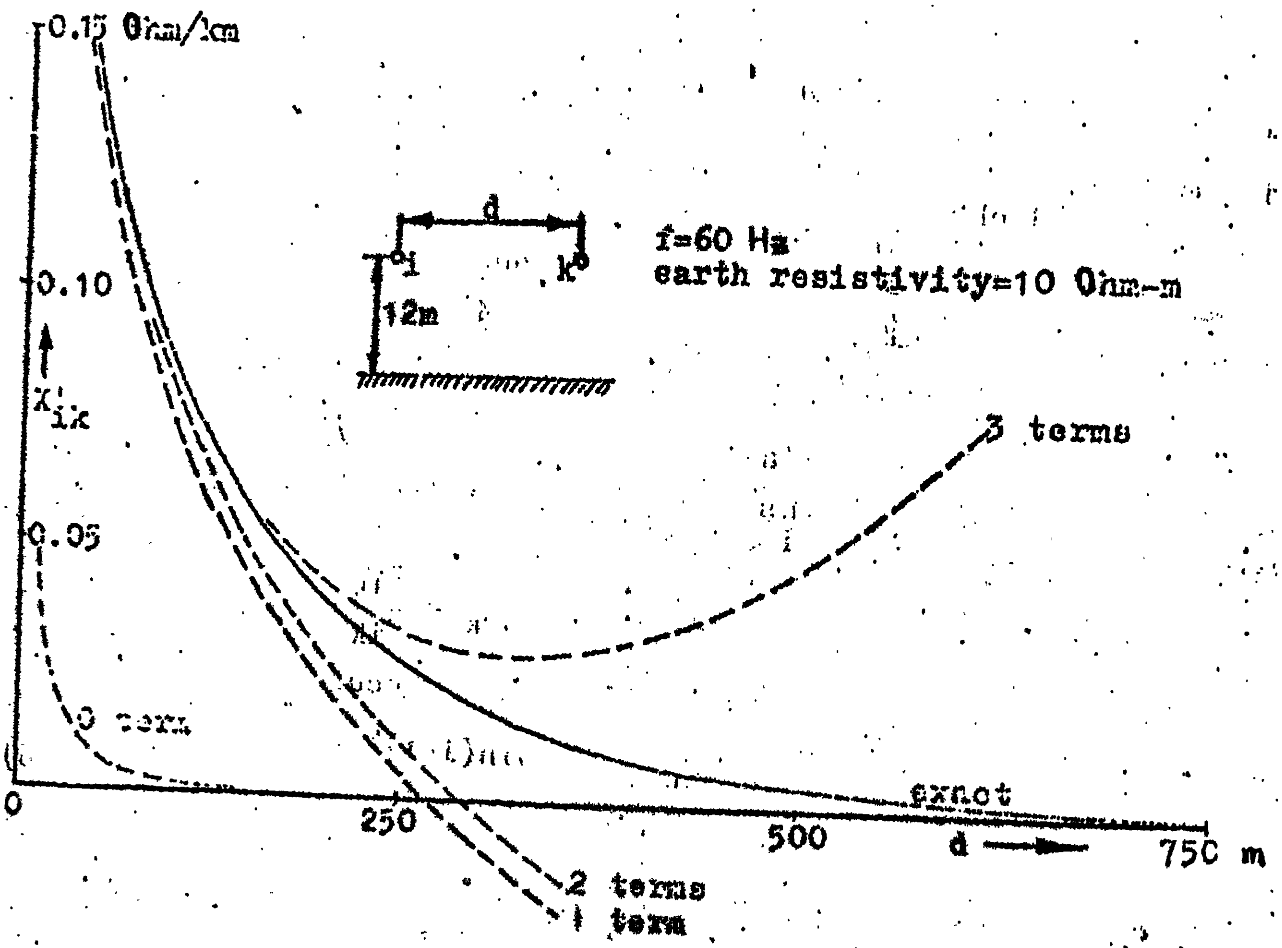


Fig.10 . Mutual reactance per unit length account. Fig. 9 shows the number of necessary terms in (33) to get the series in the brackets accurate to 2 or 3 digits behind the decimal point, with the values being of the order 0.1 and higher. Fig. 10 shows the mutual reactance as a function of spacing calculated with different numbers of terms in the series. It clearly shows that it is important to take more than the first few terms into account, even at power frequency if the spacing is wide, as in interference calculations. Once the Carson series starts to converge it does so fairly rapidly. How misleading the results with a few terms can be is shown in the following table for $a = 4$ and $\phi = 0$

Number of terms	error $\varepsilon = \frac{(\Delta R'_{ii})_{approximate}}{(\Delta R'_{ii})_{accurate}} \cdot 100$
1	311.7 %
2	-748.3 %
3	- 16.2 %
4	+798.2 %
5	-415.6 %
6	+364.9 %
7	-121.3 %
8	- 92.7 %
9	+ 27.7 %
10	- 15.0 %
11	+ 5.2 %
12	+ 1.7 %
13	- 0.35 %
14	+ 0.14 %
15	- 0.04 %

It might be more economic to substitute the infinite series of (33) with a polynomial approximation with defined error bounds; this was not explored.

b) Shunt capacitance. The capacitance matrix $[C']$ is the inverse of the matrix $[P']$ of the potential coefficients,

$$[C'] = [P']^{-1}$$

The elements of $[P']$ are calculated from the geometry. The diagonal element is

$$P'_{ii} = 18 \cdot 10^6 \ln \frac{2h_i}{r_i} \quad \text{in daraf-km} \tag{37}$$

and the off-diagonal element is

$$P'_{ik} = P'_{ki} = 18 \cdot 10^6 \ln \frac{S_{ik}}{s_{ik}} \quad \text{in daraf-km} \tag{38}$$

with r_i = radius of conductor i. The formulas are valid as long as the radii are small compared with the spacings. The exact value for the factor in (37) and (38) is $2c^2 10^{-4} \approx 18 \cdot 10^6$ with c = velocity of light in km/s.

Appendix 2. Skin effect in conductors

With increasing frequency the current is more and more crowded toward the surface of the conductor. The consequences are an increase in the resistance and a decrease in the internal inductance.

The total inductance of a nonmagnetic conductor per unit length, as used in eq.(30),

$$L'_{total} = 2 \cdot 10^{-4} \ln \frac{2h}{GMR} \quad \text{in henry/km},$$

is the result of adding the internal inductance (due to flux inside the conductor) and the external inductance (due to flux outside the conductor),

$$L'_{total} = \underbrace{2 \cdot 10^{-4} \ln \frac{r}{GMR}}_{L'_{internal}} + \underbrace{2 \cdot 10^{-4} \ln \frac{2h}{r}}_{L'_{external}} \quad \text{in henry/km}.$$

Only the internal inductance is influenced by skin effect. Since the internal inductance is only a small fraction of the total inductance, the skin effect on the total inductance is usually small, except for large conductors at high frequencies. However, skin effect on internal inductance is always taken into account (in addition to skin effect on the resistance) when asked for on the conductor card in BPA's line constants program.

When skin effect is taken into account, then the internal inductance becomes negligible at higher frequencies. Neglecting both internal inductance and earth resistivity at high frequencies, the inductance matrix $[L'] = \frac{1}{\omega} \mathrm{Im}\{Z'\}$ becomes

$$[L'] = \frac{1}{c^2}[P']$$

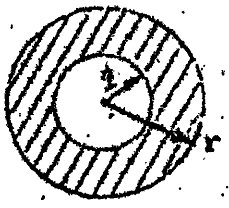
With these 2 assumptions all waves on multiphase lines will travel at the velocity of light.

The increase in the resistance because of skin effect can be considerable. For solid, round wires the skin effect formula is well known. Stranded conductors can practically be treated as solid conductors of the same cross-sectional area[4]. Steel-reinforced aluminum cables may approximately be treated as tubular conductors, when the influence of the steel core is negligible. If the magnetic material is of influence, then calculations are less reliable and measurements should be used. Since the solid conductor is a special case of the tubular conductor, the formula for the latter is given[5] for nonmagnetic material:

$$\frac{R' + j\omega L'_{internal}}{R'_{DC}} = j\frac{1}{2}mr(1-s^2)\frac{(\mathrm{ber}\,mr + j\,\mathrm{bei}\,mr) + \varphi(\mathrm{ker}\,mr + j\,\mathrm{kei}\,mr)}{(\mathrm{ber}'mr + j\,\mathrm{bei}'mr) + \varphi(\mathrm{ker}'mr + j\,\mathrm{kei}'mr)} \tag{39}$$

$$\text{with } \varphi = -\frac{\mathrm{ber}'mq + j\,\mathrm{bei}'mq}{\mathrm{ker}'mq + j\,\mathrm{kei}'mq}$$

and R' = resistance with skin effect included in ohm/km
R'_{DC} = DC-resistance in ohm/km
$L'_{internal}$ = inductance with skin effect included in henry/km
r = outside radius
q = inside radius
$s = \frac{q}{r}$
f = freq in Hz



$$(mr)^2 = k \frac{1}{1-s^2} \qquad \text{with } k = \frac{8\pi \cdot 10^{-4} f}{R'_{DC}}$$

$$(mq)^2 = k \frac{s^2}{1-s^2}$$

The modified Bessel-functions ber (...)+jbei(...), ber'(...)+jbei'(...), ker(...)+jkei(...) and ker'(...)+jkei'(...) can be calculated with polynomial approximations [16]

Note on magnetic conductors:

In eg. [39] it is assumed that the material is nonmagnetic. However, the formula is also valid for magnetic material if k is redefined:

$$k = \frac{8\pi \cdot 10^{-4} f}{R'_{DC}} \mu_r$$

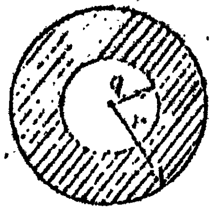
where μ_r = relative permability. Since μ_r is a function of frequency as well as a function of the current (due to saturation), no attempt was made to incorporate $\mu_r \neq 1$ into BPA's line constants program. Modifications can be made, however, for users who want to supply μ_r .

SUBROUTINE FOR SKIN EFFECT

1. Purpose: The Subroutine:

SKIN(S,R,FREQ,RF,XF)

finds the ac resistance and the internal ac reactance (explanation of "internal" in appendix 2) for tubular conductors at any frequency. The solid round conductor is a special case which is automatically included.



The first 3 arguments are input:

$S = \frac{q}{r} = \frac{\text{inner radius}}{\text{outer radius}}$

R = dc resistance in Ω/mile

FREQ = frequency in Hz

The last 2 arguments are the results:

RF = ac resistance in Ω/mile

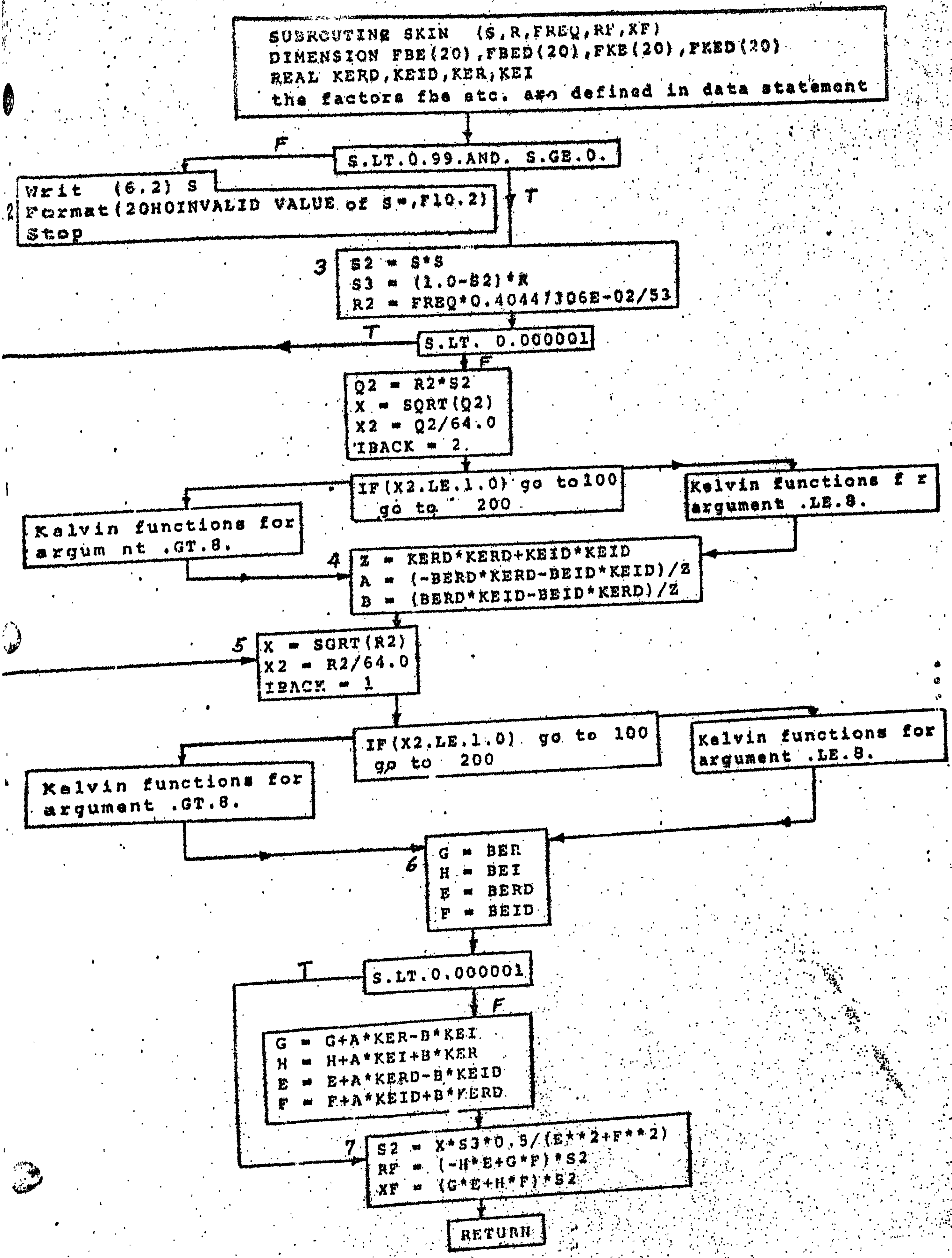
XF = ac internal reactance in Ω/mile at the specified frequency.

If ratios are desired, calculate them after execution with

$$\frac{R_{ac}}{R_{dc}} = \frac{R}{RF} \quad \text{and} \quad \frac{L_{\text{internal-ac}}}{L_{\text{internal-dc}}} = \frac{XF}{0.50559135E-3*FREQ}$$

2. Formula used: Exact formula is given in appendix 2, where the numerical procedure is also described. In the polynomial approximation from ref. 16, all Kelvin and Bessel functions are multiplied by $\exp\left(-\frac{1+j}{\sqrt{2}}x\right)$ for arguments $x > 8$ to avoid too large numbers (this factor cancels out since it shows up in the numerator and denominator of the skin effect formula).

3. Computer time: The program is in FORTRAN. One call to the subroutine takes about 0.05 s on an IBM 7040.



```
SUBROUTINE SKIN  (S,R,FREQ,RF,XF)
DIMENSION FBE(20),FBED(20),FKE(20),FKED(20)
REAL KERD,KEID,KER,KEI
the factors fbe etc. are defined in data statement
```

```
S.LT.0.99.AND. S.GE.0.
```

```
  Writ  (6,2) S
2 Format(20HOINVALID VALUE of S=,F10.2)
  Stop
```

```
3 S2 = S*S
  S3 = (1.0-S2)*R
  R2 = FREQ*0.4044/306E-02/53
```

```
S.LT. 0.000001
```

```
Q2 = R2*S2
X = SQRT(Q2)
X2 = Q2/64.0
IBACK = 2.
```

```
IF(X2.LE.1.0) go to100
  go to   200
```

```
Kelvin functions f r
argument .LE.8.
```

```
Kalvin functions for
argum nt .GT.8.
```

```
4 Z = KERD*KERD+KEID*KEID
  A = (-BERD*KERD-BEID*KEID)/Z
  B = (BERD*KEID-BEID*KERD)/Z
```

```
5 X = SQRT(R2)
  X2 = R2/64.0
  IBACK = 1
```

```
IF(X2.LE.1.0)  go to  100
 go to  200
```

```
Kelvin functions for
argument .LE.8.
```

```
Kelvin functions for
argument .GT.8.
```

```
6 G = BER
  H = BEI
  E = BERD
  F = BEID
```

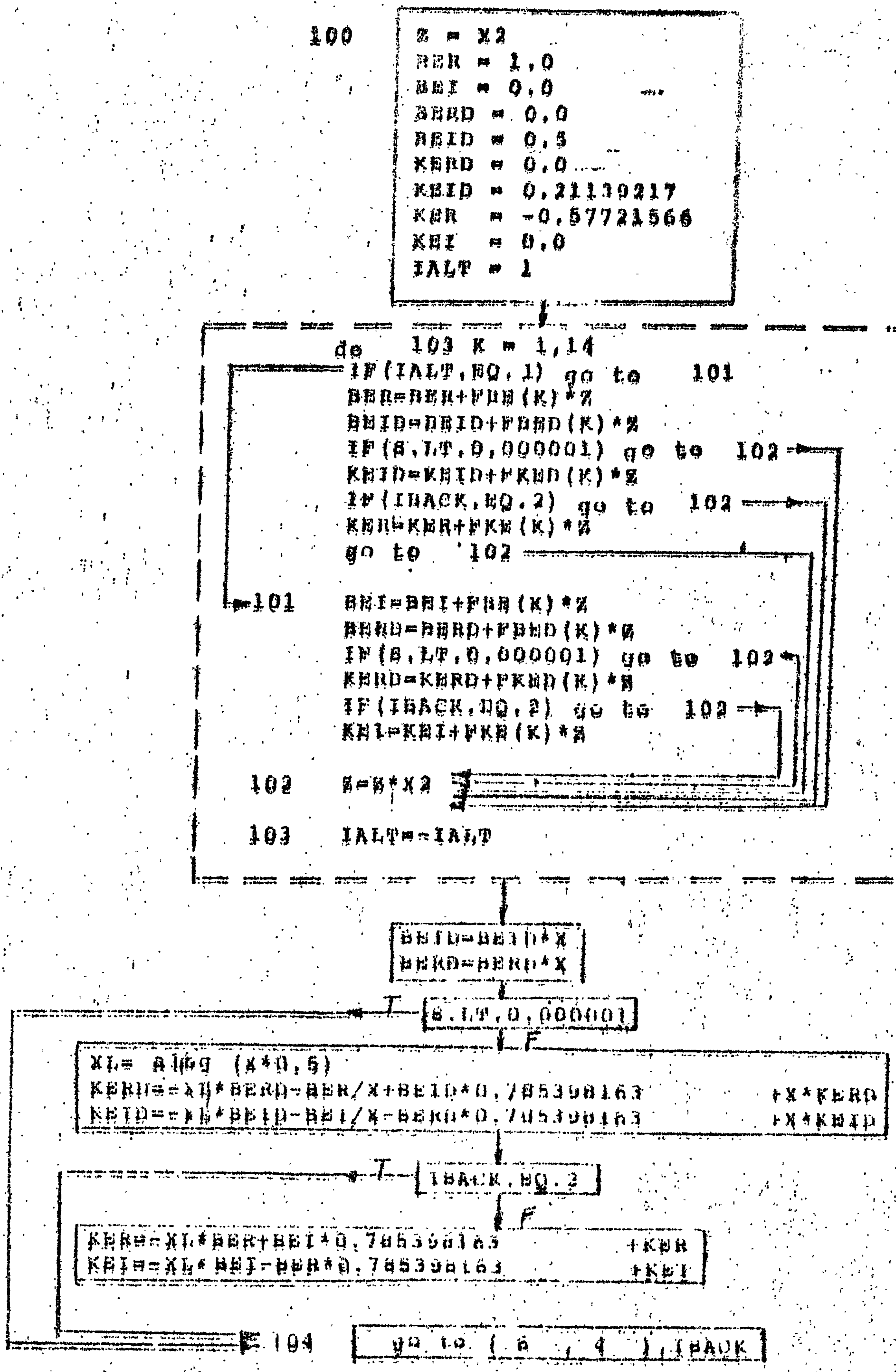
```
S.LT.0.000001
```

```
G = G+A*KER-B*KEI
H = H+A*KEI+B*KER
E = E+A*KERD-B*KEID
F = F+A*KEID+B*KERD
```

```
7 S2 = X*S3*0.5/(E**2+F**2)
  RF = (-H*E+G*F)*S2
  XF = (G*E+H*F)*S2
```

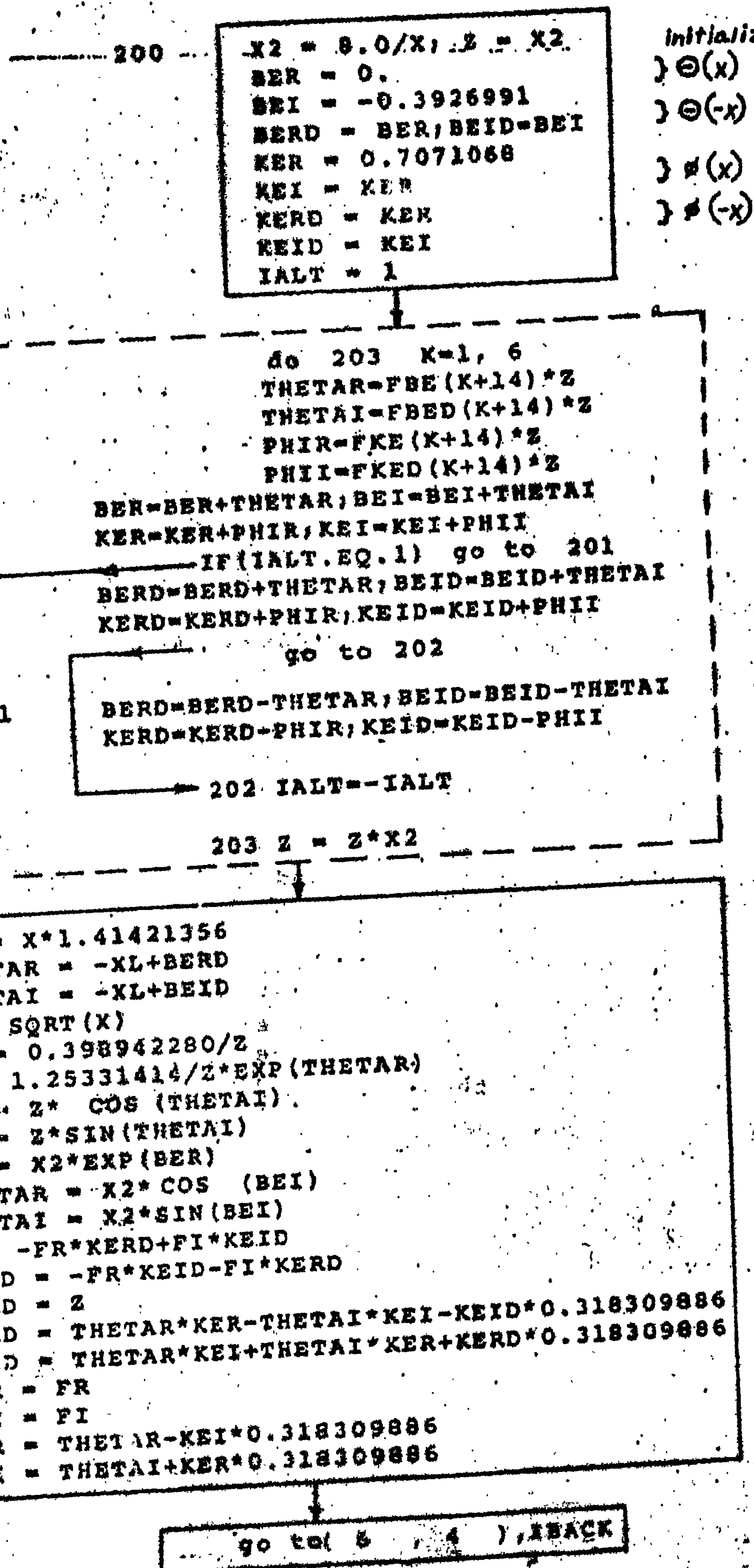
```
RETURN
```

C . CALCULATION OF KELVIN-FUNCTIONS FOR ARGUM. X .LE.8.



```
100   S = X2
      BER = 1,0
      BEI = 0,0
      BERD = 0,0
      BEID = 0,5
      KERD = 0,0
      KEID = 0,21139217
      KER  = -0,57721566
      KEI  = 0,0
      IALT = 1

      do   103 K = 1,14
           IF(IALT,EQ,1) go to   101
           BER=BER+FBR(K)*S
           BEID=BEID+FBRD(K)*S
           IF(S,LT,0,000001) go to  102
           KEID=KEID+FKED(K)*S
           IF(IBACK,EQ,2) go to  102
           KER=KER+FKE(K)*S
           go to  102

101        BEI=BEI+FBR(K)*S
           BERD=BERD+FBED(K)*S
           IF(S,LT,0,000001) go to  102
           KERD=KERD+FKED(K)*S
           IF(IBACK,EQ,2) go to  102
           KEI=KEI+FKE(K)*S

102        S=S*X2

103        IALT=-IALT

      BEID=BEID*X
      BERD=BERD*X

      S.LT.0,000001        T / F

      XL= ALOG (X*0,5)
      KERD=-XL*BERD-BER/X+BEID*0,785398163          +X*KERD
      KEID=-XL*BEID-BEI/X-BERD*0,785398163          +X*KEID

      IBACK.EQ.2           T / F

      KER=-XL*BER+BEI*0,785398163          +KER
      KEI=-XL*BEI-BER*0,785398163          +KEI

104   go to ( 6 , 4 ),IBACK
```

C CALCULATIONS OF KELVIN-FUNCTIONS FOR ARGUMENT.GT.8



```
200   X2 = 8.0/X; Z = X2
      BER = 0.
      BEI = -0.3926991
      BERD = BER;BEID=BEI
      KER = 0.7071068
      KEI = KER
      KERD = KER
      KEID = KEI
      IALT = 1

            do 203  K=1, 6
            THETAR=FBE(K+14)*Z
            THETAI=FBED(K+14)*Z
            PHIR=FKE(K+14)*Z
            PHII=FKED(K+14)*Z
      BER=BER+THETAR;BEI=BEI+THETAI
      KER=KER+PHIR;KEI=KEI+PHII
            IF(IALT.EQ.1)  go to  201
      BERD=BERD+THETAR;BEID=BEID+THETAI
      KERD=KERD+PHIR;KEID=KEID+PHII
            go to 202
201   BERD=BERD-THETAR;BEID=BEID-THETAI
      KERD=KERD-PHIR;KEID=KEID-PHII
202   IALT=-IALT
203   Z = Z*X2

      XL = X*1.41421356
      THETAR = -XL+BERD
      THETAI = -XL+BEID
      Z = SQRT(X)
      X2 = 0.398942280/Z
      Z = 1.25331414/Z*EXP(THETAR)
      FR = Z*  COS (THETAI)
      FI = Z*SIN(THETAI)
      X2 = X2*EXP(BER)
      THETAR = X2* COS  (BEI)
      THETAI = X2*SIN(BEI)
      Z = -FR*KERD+FI*KEID
      KEID = -FR*KEID-FI*KERD
      KERD = Z
      BERD = THETAR*KER-THETAI*KEI-KEID*0.318309886
      BEID = THETAR*KEI+THETAI*KER+KERD*0.318309886
      KER = FR
      KEI = FI
      BER = THETAR-KEI*0.318309886
      BEI = THETAI+KER*0.318309886

      go to( 5  , 4  ),IBACK
```

initializing for:

} $\Theta(x)$

} $\Theta(-x)$

} $\phi(x)$

} $\phi(-x)$

} $\frac{1}{\sqrt{2\pi x}}$ *real part*

} $\sqrt{\frac{\pi}{2x}}\cdot e$

} $f(x)$

} $g(x)$

} $ker' + j\, kei'$

APPENDIX 3

Note on Attenuation in Overhead Lines

References: [1] Goldstein, A.: "Propagation Characteristic of Power Line Carrier Links," Brown-Boveri Review, Vol. 35, 1948, P. 266.

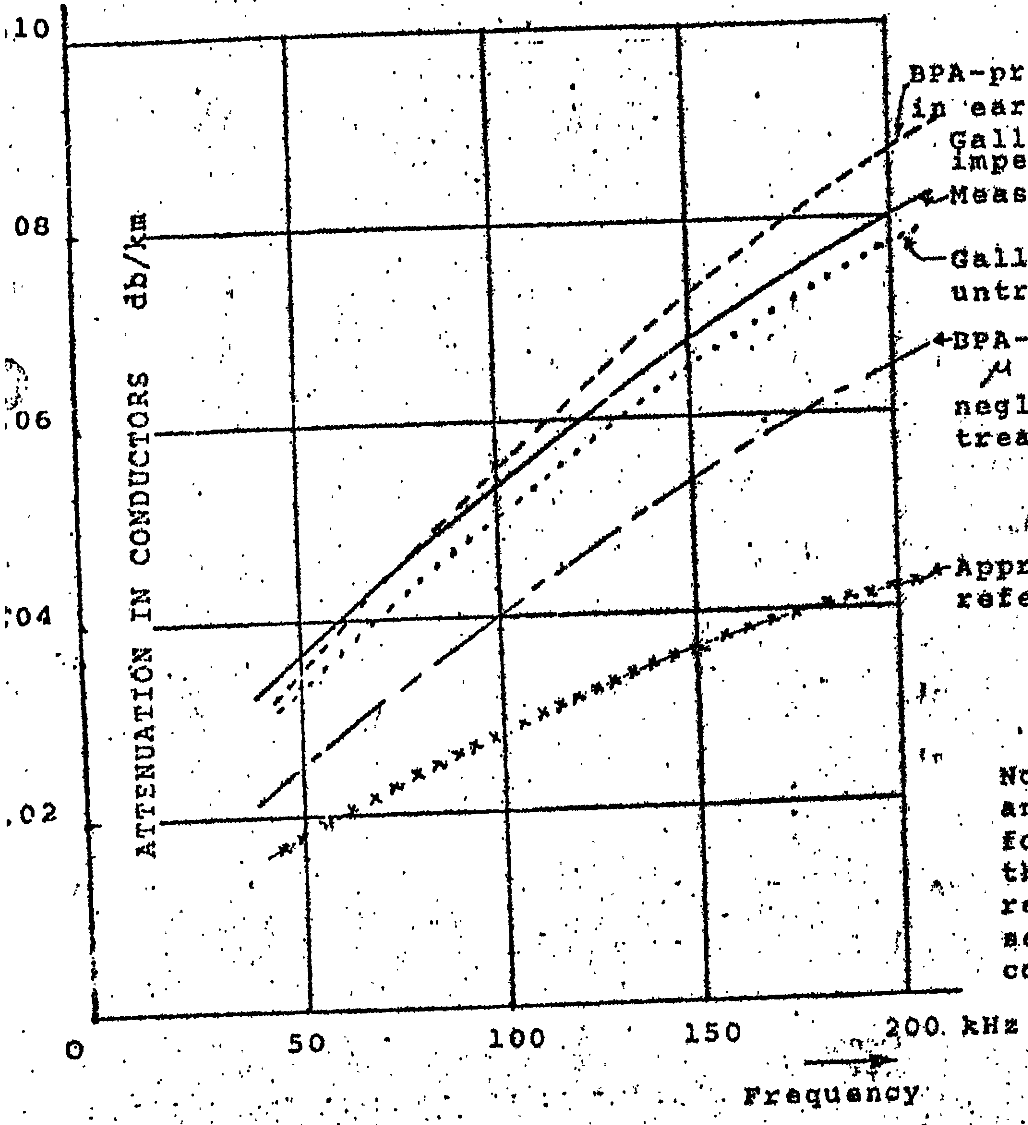
[2] Galloway, R. H., W. B. Shomocks, and L. M. Wedepohl: "Calculation of Electrical Parameters for Short and Long Polyphase Transmission Lines", Proc. IEE (London), Vol. 111, No. 12, pp. 2051-2059, December 1964.

[3] User's Manual for Line Constants. Memo of the Methods Analysis Group.

Reference 1 contains measurements and approximate formulas for the attenuation on an untransposed line. The values were re-computed in reference 2 with more accurate formulas.

The same case was run with BPA's line constants program (reference 3); a slight modification was made to handle μ = 1000 in the earth wire (the normal program version assumes μ = 1). Also, the positive sequence data were considered to be close enough to the data of mode-2-propagation (one of 3 independent modes; mode 2 not associated with ground return) of reference 2. The modes could be found by an eigenvalue analysis; this is not included in the line-constants-program as of now.

BPA's line constants program neglects stranding and assumes a round conductor (or tubular when the steel core of an ACSR is ignored). When Galloway's formula for the internal impedance of stranded conductors is used, then BPA results come very close to measurements. Unfortunately, Galloway's formula contains a factor which must be found from measurements in an electrolytic tank. Galloway says that his factor of 2.25 is satisfactory for the number of outer strands being 6, 12, 18 or 24 and for frequencies above 2-5 KHz. It was also tried to treat each strand as an individual conductor and bundle them. The results were unsatisfactory (lay in neighborhood of approximate formula of reference 1); this is probably due to high proximity effects which are not taken into account in the line constants program.



BPA-program, modified for μ =1000 in earth wire, and using Galloway's formula for internal impedances

Measured (reference 1)

Galloway's results for untransposed line, mode 2

BPA-program, modified for μ =1000 in earth wire, neglecting stranding (conductor treated as solid round)

Approximate formula in reference 1

Note: Galloway's results and the measurements are for mode 2 propagation of the untransposed line, BPA results are for positive sequence (using the line constants program).

Appendix 4. Matrix reduction and matrix inversion

Explanation of matrix reduction

Given a system of linear equations:

$$[A][x] = [b]$$

with $[A]$ = $n \times n$ matrix

$[x], [b]$ = vectors with n components.

Let the components in the vectors be subdivided into 2 subsets 1 and 2. With the corresponding subdivision in the matrices we get

$$\begin{bmatrix} [A_{11}] & [A_{12}] \\ {[A_{21}]} & [A_{22}] \end{bmatrix} \begin{bmatrix} [x_1] \\ {[x_2]} \end{bmatrix} = \begin{bmatrix} [b_1] \\ {[b_2]} \end{bmatrix} \quad \text{or} \quad \begin{aligned} &[A_{11}][x_1]+[A_{12}][x_2] = [b_1] &\quad (\text{IV},1)\\ &[A_{21}][x_1]+[A_{22}][x_2] = [b_2] &\quad (\text{IV},2)\end{aligned}$$

The objective is to arrive at a reduced system of equations for subset 1. This is accomplished by solving (IV,2) for $[x_2]$,

$$-[A_{22}]^{-1}[A_{21}][x_1] + [A_{22}]^{-1}[b_2] = [x_2] \qquad (\text{IV},3)$$

and inserting this into (IV,1), which becomes

$$[A_{11}^{\text{reduced}}][x_1] = [b_1] + [D_{12}][b_2] \qquad (\text{IV},4)$$

with the reduced matrix $[A_{11}^{\text{reduced}}] = [A_{11}] - [A_{12}][A_{22}]^{-1}[A_{21}]$

(sometimes called "Kron's reduction formula")

and the distribution factor matrix

$$[D_{12}] = -[A_{12}][A_{22}]^{-1}.$$

Eq. (IV,4) becomes quite simple if $[b_2] = 0$. In this case

$$[A_{11}^{\text{reduced}}][x_1] = [b_1] \qquad \text{if } [b_2] = 0 \qquad (\text{IV},5)$$

Whenever equations are to be reduced in this text, they will first be brought into a form where $[b_2] = 0$ to arrive at the simple reduced system (IV,5) where no distribution factors are necessary.

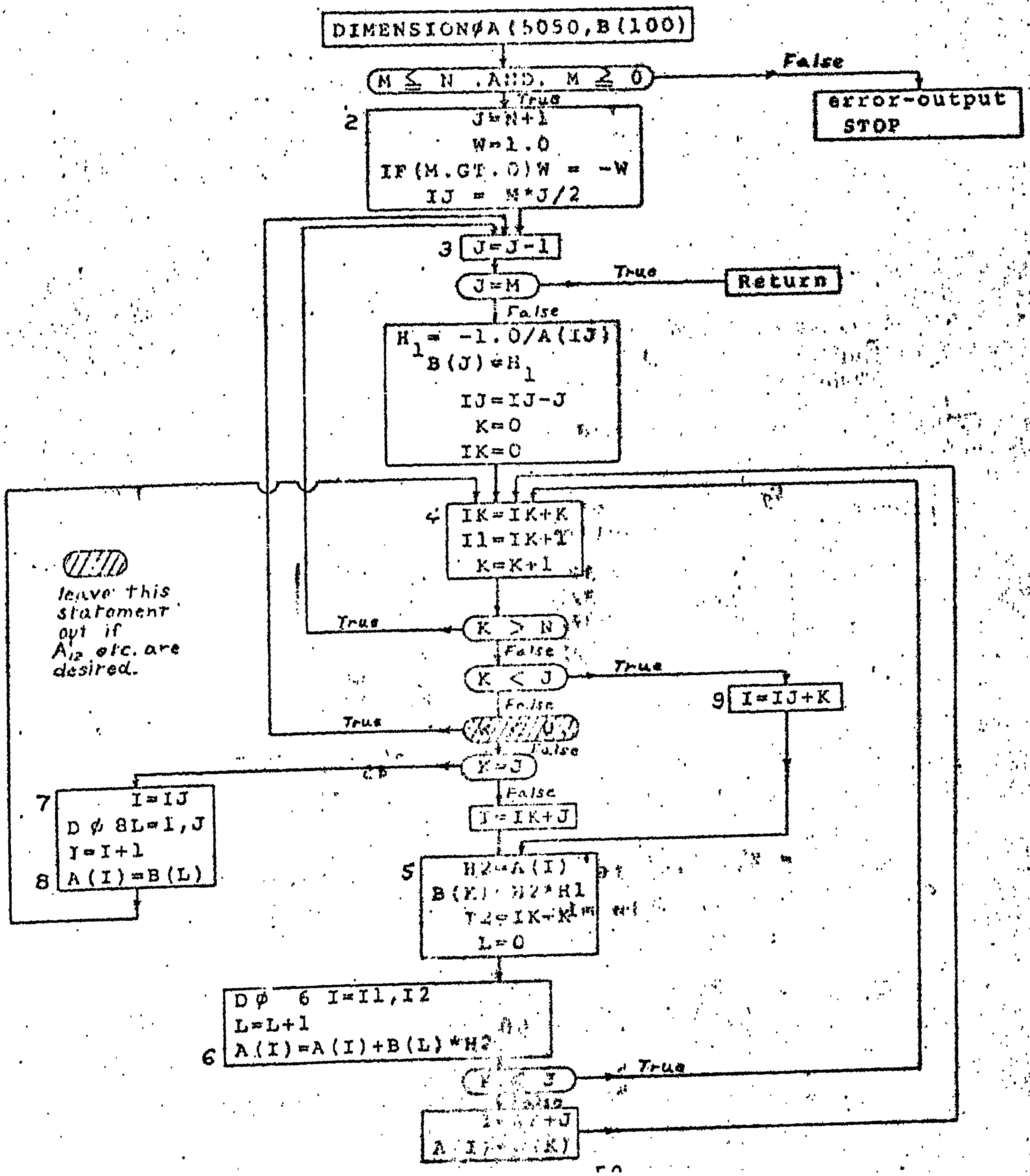
Flow Chart for CT (A,N,M)

Matrix is reduced from size N to size M. Variables $X_{m+1}, \ldots X_n$ are eliminated. If M=0: result is negative inverse matrix.

Note: The reduction or inversion process yields the system of equations

$$\begin{bmatrix} [A_{11}\,\text{reduced}] & -[D_{12}] \\ -[D_{12}]^T & [A_{22}]^{-1} \end{bmatrix} \begin{bmatrix} [X_1] \\ [b_2] \end{bmatrix} = \begin{bmatrix} [b_1] \\ [X_2] \end{bmatrix}$$

and replaces the original matrix with the one shown at left. In case of reduction (M > 0) only $[A_{11}\,\text{reduced}]$ is normally produced. If the other submatrices $-[D_{12}]^T$ and $[A_{22}]^{-1}$ are also desired, then leave out the shaded statem nt as indicated below.

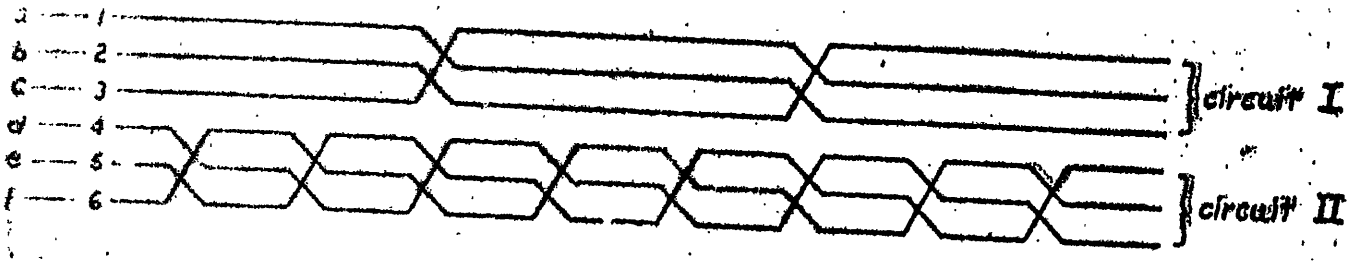


Appendix

Transposition of Double Circuits

1. Double circuit, transposition scheme f 9 sections

A perfect decoupling of the sequence quantities within each 3-phase circuit and also a decoupling between the 2 circuits except for the zero sequence is reached by the following transposition scheme:



The symmetrical component matrix will have zero elements except for:

$$
\begin{array}{lll}
Z'_{zero-I} & Z'_{zero-II} & \text{and } Z'_{zero-I/II} \\
Z'_{pos.-I} & Z'_{pos.-II} & \\
Z'_{neg.-I} & Z'_{neg.-II} &
\end{array}
$$

There is no cross-coupling from one sequence to another and also no coupling within the same sequence between the 2 circuits except in the zero-sequence.

Using the same approach of adding the voltage drops for all sections, one gets

$$
\left[Z'_{phase}\right] = 1/9 \left\{ \begin{bmatrix} Z'_{phase\ of} \\ \text{1st section} \end{bmatrix} + \begin{bmatrix} Z'_{phase\ of} \\ \text{2nd section} \end{bmatrix} + \cdots \begin{bmatrix} Z'_{phase\ of} \\ \text{9th section} \end{bmatrix} \right\}
$$

$$
= 1/9 \left[\begin{array}{ccc:ccc}
3Z'_{BI} & 3Z'_{AI} & 3Z'_{AI} & Z'_c & Z'_c & Z'_c \\
3Z'_{AI} & 3Z'_{BI} & 3Z'_{AI} & Z'_c & Z'_c & Z'_c \\
3Z'_{AI} & 3Z'_{AI} & 3Z'_{BI} & Z'_c & Z'_c & Z'_c \\
\hdashline
Z'_c & Z'_c & Z'_c & 3Z'_{BII} & 3Z'_{AII} & 3Z'_{AII} \\
Z'_c & Z'_c & Z'_c & 3Z'_{AII} & 3Z'_{BII} & 3Z'_{AII} \\
Z'_c & Z'_c & Z'_c & 3Z'_{AII} & 3Z'_{AII} & 3Z'_{BII}
\end{array} \right]
$$

with $Z'_{AI} = Z'_{12}+Z'_{23}+Z'_{31}$ $\quad Z'_{AII} = Z'_{45}+Z'_{56}+Z'_{64}$

$Z'_{BI} = Z'_{11}+Z'_{22}+Z'_{33}$ $\quad Z'_{BII} = Z'_{44}+Z'_{55}+Z'_{66}$

and $Z'_c = Z'_{14}+Z'_{15}+Z'_{16}+Z'_{24}+Z'_{25}+Z'_{26}+Z'_{34}+Z'_{35}+Z'_{36}$

bearing in mind that $Z'_{ik} = Z'_{ki}$

Transforming into symmetrical components yields:

$$\left[Z'_{symm.}\right] = \left[\begin{array}{c|c} S^{-1} & 0 \\ \hline 0 & S^{-1} \end{array}\right] \cdot \left[Z'_{phase}\right] \cdot \left[\begin{array}{c|c} S & 0 \\ \hline 0 & S \end{array}\right]$$

$$= \left[\begin{array}{ccc|ccc} \frac{Z'_{BI}+2Z'_{AI}}{3} & 0 & 0 & \frac{Z'_{C}}{3} & 0 & 0 \\ 0 & \frac{Z'_{BI}-Z'_{AI}}{3} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{Z'_{BI}-Z'_{AI}}{3} & 0 & 0 & 0 \\ \hline \frac{Z'_{C}}{3} & 0 & 0 & \frac{Z'_{BII}+2Z'_{AII}}{3} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{Z'_{BII}-Z'_{AII}}{3} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{Z'_{BII}-Z'_{AII}}{3} \end{array}\right] \quad (V,1)$$

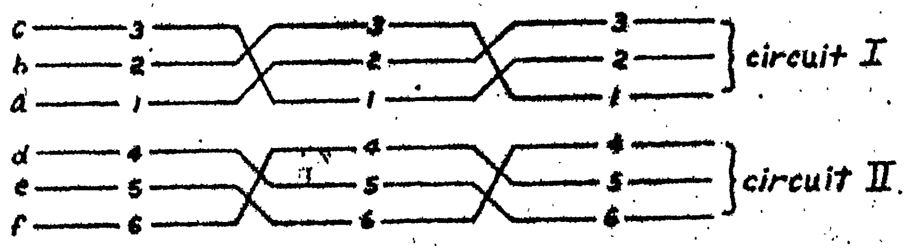
It can easily be verified that the non-zero elements in (V,3) come out identically when the line-constants program for untransposed configuration is used. Therefore, again simply

> ignore the terms in the untransposed series impedance and shunt capacitance matrices for the symmetrical components in the places of zero-entries in (V,3) to account for the transposition effect

2 Double Circuit, Transposition in 3 Sections in Opposite Direction,

The cross-coupling from one sequence to another can also be avoided by a much simpler transposition scheme with rotation in opposite direction. It leaves coupling within the same sequence between the 2 circuits however.

Scheme:



Note that the conductors are numbered in the order of the phases a,b,c and d,e,f in th first section

First find

$$[Z'_{phase}] = \frac{1}{3}\left[\begin{array}{ccc|ccc} Z'_{BI} & Z'_{AI} & Z'_{AI} & Z'_K & Z'_L & Z'_M \\ Z'_{AI} & Z'_{BI} & Z'_{AI} & Z'_M & Z'_K & Z'_L \\ Z'_{AI} & Z'_{AI} & Z'_{BI} & Z'_L & Z'_M & Z'_K \\ \hline Z'_K & Z'_M & Z'_L & Z'_{BII} & Z'_{AII} & Z'_{AII} \\ Z'_L & Z'_K & Z'_M & Z'_{AII} & Z'_{BII} & Z'_{AII} \\ Z'_M & Z'_L & Z'_K & Z'_{AII} & Z'_{AII} & Z'_{BII} \end{array}\right] \qquad (V,4)$$

with $Z'_{AI} = Z'_{12}+Z'_{23}+Z'_{31}$ $\qquad Z'_{AII} = Z'_{45}+Z'_{56}+Z'_{64}$

$Z'_{BI} = Z'_{11}+Z'_{22}+Z'_{33}$ $\qquad Z'_{BII} = Z'_{44}+Z'_{55}+Z'_{66}$ $\qquad$ (V,5)

$Z'_K = Z'_{14}+Z'_{25}+Z'_{36}$

$Z'_L = Z'_{15}+Z'_{26}+Z'_{34}$ $\qquad Z'_L = Z'_M$ of same configuration in both circuits

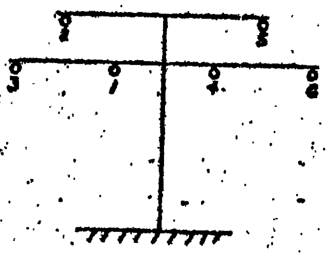
$Z'_M = Z'_{16}+Z'_{24}+Z'_{35}$

Then transforming into symmetrical components yields:

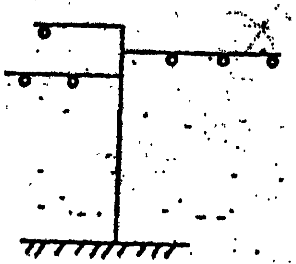
$$[Z'_{symm.}] = \left[\begin{array}{c|c} S^{-1} & 0 \\ \hline 0 & S^{-1} \end{array}\right] \cdot [Z'_{phase}] \cdot \left[\begin{array}{c|c} S & 0 \\ \hline 0 & S \end{array}\right]$$

$$[Z'_{symm.}] = \left[\begin{array}{ccc|ccc} \frac{Z'_{BI}+2Z'_{AI}}{3} & 0 & 0 & \frac{Z'_K+Z'_L+Z'_M}{3} & 0 & 0 \\ 0 & \frac{Z'_{BI}-Z'_{AI}}{3} & 0 & 0 & \frac{Z'_K+a^2Z'_L+aZ'_M}{3} & 0 \\ 0 & 0 & \frac{Z'_{BI}-Z'_{AI}}{3} & 0 & 0 & \frac{Z'_K+aZ'_L+a^2Z'_M}{3} \\ \hline \frac{Z'_K+Z'_L+Z'_M}{3} & 0 & 0 & \frac{Z'_{BII}+2Z'_{AII}}{3} & 0 & 0 \\ 0 & \frac{Z'_K+aZ'_L+a^2Z'_M}{3} & 0 & 0 & \frac{Z'_{BII}-Z'_{AII}}{3} & 0 \\ 0 & 0 & \frac{Z'_K+a^2Z'_L+aZ'_M}{3} & 0 & 0 & \frac{Z'_{BII}-Z'_{AII}}{3} \end{array}\right]$$

Eq. (V,6) shows that within each sequence there is coupling from one circuit (I) to the other (II). Theoretically $Z'_{pos.\ I-II} = Z'_{pos.\ II-I}$ (same true for negative sequence coupling from I to II), however, in tractical cases the conductor arrangement is likely to be symmetric with respect to the tow r



symmetric



unsymmetric

For symmetric arrangement:

$Z'_L = Z'_M$ and therefore:

$$Z'_{pos.I-II} = Z'_{pos.\ II-I} = $$

$$= Z'_{neg.I-II} = Z'_{neg.\ II-I} = \frac{Z'_K - Z'_L}{3}$$

Again it can easily b verified that the line-constants program for untransposed configuration yields the same values in the non-zero entries in (V,6).

Verification by computing

$$\left[\begin{array}{c|c} S^{-1} & 0 \\ \hline 0 & S^{-1} \end{array}\right] \cdot \left[\begin{array}{ccccc} Z'_{11} & Z'_{12} & Z'_{13} & \dots & Z'_{16} \\ Z'_{21} & Z'_{22} & Z'_{23} & \dots & Z'_{26} \\ \hline Z'_{61} & Z'_{62} & Z'_{63} & \dots & Z'_{66} \end{array}\right] \left[\begin{array}{c|c} S & 0 \\ \hline 0 & S \end{array}\right]$$

Th refore again simply

> ignore the terms in the untransposed series impedance and shunt capacitance matrices for the symmetrical components in the places of zero-entries in (V,6) to account for the transposition effect.
>
> Attention: Number phases as in first section to express opposite directions for transpositions

Appendix 6

Series Connection of Two Identical Equivalent multi-π's

The series connection of two identical multi- π's (Fig. 7, p. 21) is described by the equations

$$\begin{bmatrix} [Y_{11}] & 0 & [Y_{12}] \\ 0 & [Y_{11}] & [Y_{12}] \\ [Y_{12}] & [Y_{12}] & 2[Y_{11}] \end{bmatrix} \begin{bmatrix} [V_1] \\ [V_2] \\ [V_3] \end{bmatrix} \begin{bmatrix} [I_1] \\ [I_2] \\ 0 \end{bmatrix} \qquad (40)$$

with $[Y_{11}] = [Y_{transfer}] + [Y_{shunt}]$ and $[Y_{12}] = -[Y_{transfer}]$. (41)

The elimination of the node voltages in ③ yields:

$$\begin{bmatrix} [Y_{11}^{double}] & [Y_{12}^{double}] \\ [Y_{12}^{double}] & [Y_{11}^{double}] \end{bmatrix} \times \begin{bmatrix} [V_1] \\ [V_2] \end{bmatrix} = \begin{bmatrix} [I_1] \\ [I_2] \end{bmatrix} \qquad (42)$$

with $[Y_{12}^{double}] = -1/2\,[Y_{12}]\,[Y_{11}]^{-1}\,[Y_{12}]$ (43)

$[Y_{11}^{double}] = [Y_{11}] + [Y_{12}^{double}]$.

Because of the structure of (40), it is possible to carry out the elimination in a 2M x 2M matrix instead of a 3M x 3M matrix. To do this, take the system

$$\begin{bmatrix} [Y_{11}] & [Y_{12}] \\ [Y_{12}] & 2[Y_{11}] \end{bmatrix} \times \begin{bmatrix} [X_1] \\ [X_2] \end{bmatrix} = \begin{bmatrix} [Y_1] \\ 0 \end{bmatrix} \tag{44}$$

and eliminate $[X_2]$, which yields

$$\left\{[Y_{11}] - 1/2\ [Y_{12}]\ [Y_{11}]^{-1}\ [Y_{12}]\right\}[X_1] = [Y_1] \tag{45}$$

This is the desired matrix $[Y_{11}^{double}]$. Then $[Y_{12}^{double}]$ is simply the difference

$$[Y_{12}^{double}] = [Y_{11}^{double}] - [Y_{11}] \tag{46}$$

Appendix 7

Choice of Incremental Length Δs

The incremental length Δs for the initial equivalent of eq. (27) must be chosen small enough to justify the use of eq. (29); that is an upper bound, based on the comparison of Δs with the wave length, must be observed. There is also a lower bound, determined by round-off problems, which must be observed. This lower bound is estimated pragmatically in the following way:

As seen in (40) of appendix 6, a sum

$$[Y_{transfer}] + [Y_{shunt}]$$

enters the admittance matrix, with each term found from eq. (29). Clearly, the first term gets larger and larger as Δs decreased and the second term gets smaller and smaller as Δs decreases. Because of the finite number of digits in a computer, $[Y_{shunt}]$ would finally get lost in the summation if Δs is too small (with $Y_{transfer} = 1$ and $Y_{shunt} = 10^{-8}$ a 6-digit-computer would loose Y_{shunt} and give $Y_{transfer} + Y_{shunt} = 1$).

From experiments on an IBM 7040 (with about 9 significant decimal digits) a good choice of Δs was a value that makes $Y_{shunt} \approx 0.5\ 10^{-3} Y_{transfer}$. This choice avoids the loss of too many significant digits in Y_{shunt} in the summation and also avoids an excessive number of doubling procedures in getting the equivalent for the total length, which is also a source of round-off errors. For the general case of multiphase lines (including the single-phase line), values Δs_i are found from comparison of the diagonals only, in the equation,

$Y_{ii_{shunt}} = 0.5\ 10^{-3}\ Y_{ii_{transfer}}$, from which the smallest value is selected as a first guess, $\Delta s_{guess} = \min\{\Delta s_i\}$.

Since the successive doubling should lead to the exact length S, the value used for Δs is the value Δs_{guess} decreased until

Δs x (power of 2) = S.

Example: Three-phase line with S=800 miles, $\Delta s_1 = 9.5$, $\Delta s_2 = 8$, $\Delta s_3 = 10.2$ miles, then $\Delta s_{guess} = 8$ miles, then $\Delta s = 6.25$ miles. For 60 Hz Δs is usually of the order of 10 miles with this procedure.

REFERENCES

1. D. Coleman, F. Watts, and R.B. Shipley, "Digital calculation of overhead-transmission-line constants," AIEE Trans., pt. III (Power Apparatus and Systems), vol.77, pp. 1266-1270, 1958.

2. M.H. Hesse, "Electromagnetic and electrostatic transmission-line parameters by digital computer," IEEE Trans. Power Apparatus and Systems, vol.82, pp. 282-290, 1963.

3. R.B. Shipley, and D.W. Coleman, "A new direct matrix inversion method," AIEE Trans., pt.I (Commun. and Electronics), vol.78, pp. 568-572, 1959.

4. W.I. Bowman, and J.M. McNamee, "Development of equivalent Pi and T matrix circuits for long untransposed transmission lines," IEEE Trans. Power Apparatus and Systems, vol.83, pp. 625-632, discussion pp. 653-657, 1964.

5. E. Bodewig, Matrix Calculus, 2nd edition. Amsterdam: North-Holland Publishing Co., 1959, p. 115.

6. E. Clarke, Circuit Analysis of A-C Power Systems, vol.I. New York: John Wiley and Sons, 1943, p. 457.

7. W.S. Meyer and H.W. Dommel, "Telephone-interference calculation for multiconductor power lines," IEEE Trans. Power Apparatus and Systems, vol.88, pp. 35-41, January 1969.

8. J.G.F. Francis, "The QR transformation," Computer Journal, Vol.4, pp. 332-345, 1961.

9. J.H. Wilkinson, The Algebraic Eigenvalue Problem. London: Oxford University Press, 1965.

10. M.C. Perz, "Natural modes of power line carrier on horizontal three-phase lines," IEEE Trans. Power Apparatus and Systems, vol.83, pp. 679-686, discussion pp. 748-754, 1964.

11. M.C. Perz, "A method of analysis of power line carrier problems on three-phase lines," IEEE Trans. Power Apparatus and Systems, vol.83, pp. 686-691, discussion pp. 754-756, 1964.

12. J.R. Carson, "Wave propagation in overhead wires with ground return," Bell System Technical Journal, vol.5, pp. 539-554, 1926.

13. S. Butterworth, Electrical characteristics of overhead lines, El. Research Association, Techn. Report Ref. O/T4, 1954.

14. A.E. Kennelly, F.A. Laws, and P.H. Pierce, "Experimental research on skin effect in conductors," AIEE Trans., pt.II, vol.34, pp. 1953-2018, 1915.

15. H.B. Dwight, Electrical Coils and Conductors. New York: McGraw Hill Book Co., 1945, p. 171 or:

N.W. Mclachlan, Bessel Functions for Engineers. Oxford: Clarendon Press, 1955, p. 176.

16. Handbook of Mathematical Functions. Edited by M. Abramowitz and I.A. Stegun, publ. by US Dept. of Commerce, 1964, pp. 384-385 (note: for arguments x greater 8 the functions are better multiplied by $\exp\left(\frac{-1+j}{\sqrt{2}}x\right)$ to avoid too large numbers).

17. L.M. Wedepohl, "Electric characteristics of polyphase transmission systems with special reference to boundary-value calculations at power-line carrier frequencies," Proc. IEE, vol.112, pp. 2103-2112, 1965.

18. O. Nigol, "Analysis of radio noise from high-voltage lines (II) - Propagation theory," IEEE Trans. Power Apparatus and Systems, vol.83, pp. 533-541, discussion pp. 554-558, 1964.

19. L.M. Wedepohl, and J.N. Saha, "Radio-interference fields in multi-conductor overhead transmission lines," Proc. IEE, vol.116, pp. 1875-1884, November 1969.

20. L.M. Wedepohl, "Application of matrix methods to the solution of travelling-wave phenomena in polyphase systems," Proc. IEE, vol.110, pp. 2200-2212, December 1963.

21. H. Holley, D. Coleman, and R.B. Shipley, "Untransposed EHV line computations," IEEE Trans. Power Apparatus and Systems, vol.83, pp. 291-296, discussion pp. 300-304, 1964.

22. EHV Transmission Line Reference Book. New York: Edison Electric Institute, 1968.

7.5 "SEMLYEN SETUP" Routine

By means of the special request word "SEMLYEN SETUP" , an EMTP user gains access to the supporting routine which bears this same name, as per the explanation of Section 7. . The principal function of this code is to punch the branch cards which are needed for the representation of a transmission circuit using Semlyen Recursive Convolution modeling. See Section 1.27

Note : The "SEMLYEN SETUP" code which is now to be described is essentially the same as in November of 1977 (time of "M21." versions). Representation of the propagation response and the admittance response is limited to just two real exponentials each, and time-domain fitting is used. On the other hand, the solution mathematics of Section 1.27 allow an arbitrary number of complex exponentials. The old "SEMLYEN SETUP" overlay has simply been interfaced with the new simulation code, so that it can continue to be used Read further perspective at the very end of this section (page 215).

7.5-A Structure of "SEMLYEN SETUP" data deck

Suppose that the user wants to use the "SEMLYEN SETUP" routine. His input data cards are then to be structured as follows:

S1. First comes a "BEGIN NEW DATA CASE" card (actually optional, as per Section 1.0a).

S2. Next comes a "SEMLYEN SETUP" card, which serves to transfer control to the overlay in question (UTPF overlay number 45).

S3. Next come optional special-request cards (if any), in arbitrary order. Such data cards are recognized by usage of one of the following special-request words which begin in column number 1:

a) "BRANCH" ——— to name the nodes (A6 information) at each end of each phase of the transmission circuit.

b) "TOLERANCES" —— to redefine one or more of the numerous "constants" which control the logic of this routine.

S4. Next comes a miscellaneous data card.

S5. Next come three extensions to the miscellaneous data card, *if and only if* miscellaneous data parameter "IOTX" was given the value -1 . These three cards (if so used) provide an expanded format for redefinition of the miscellaneous data parameters "IOTX" , "IOSS" , and "IOFL" .

S6. One single, complete data case for "LINE CONSTANTS" or "CABEL CONSTANTS". The first card of this grouping must read "LINE CONSTANTS" or "CABLE CONSTANTS" ; two blank cards will end the grouping (the first to end frequency cards, and the second to end data cases within the supporting program in question). The frequency cards should be prepared according the following order and rules:

Untransposed line (or cable) --- THREE frequency cards are needed:

1. The first frequency card is for the calculation of the modal-phase domain transformation matrix at a specified frequency FREQ. The default value for FREQ is set to be 5000 Hz. To calculate this transformation matrix at a frequency other than 5000 Hz, one needs to enter the desired value in the field of FREQ on this frequency card, and to redefine FMED with this same value on the "TOLERANCES" card (see section 7.5-B).

2. The second frequency card is for the steady state frequency at which the resulting line (or cable) model is to be used. This is usually 50 Hz or 60 Hz for ac systems. For dc systems, use some small value such as .001 Hz.

3. The third frequency card is to request the logarithmic looping over all frequencies which are required by the inverse Fourier transformation of "SEMLYEN SETUP". Typically this will provide for 20 points per decade, beginning at 1 Hz and ending at 10^7 Hz.

Transposed line (or cable) --- Only TWO, namely the second and the third of the aforementioned frequency cards are needed.

S7. Repeat the data of Point S3 through Point S6 as often as is desired. Each such grouping represents a separat data case within "SEMLYEN SETUP" .

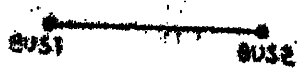
Actually, the cards of Point S6 are to be omitted in such a data grouping if and only if either the "NEW RHO" or the "OLD DATA" option is being used. In such cases, the geometrical data of the transmission circuit is "remembered" from the preceding data case within "SEMLYEN SETUP" . By using one of these options, as few as a single data card can constitute a data case within "SEMLYEN SETUP" (only the miscellaneous data card is mandatory).

S8. If the user wants to shut the EMTP off at this point (rather than execute a following EMTP data case), he should simply add a "BEGIN NEW DATA CASE" card at this point, followed by a blank card. This is as per Section 1.0b .

7.5-B Format for data cards of "SEMLYEN SETUP"

1) "BRANCH" card (Point S3-a data)

BRANCH	A6	A6	A6	A6	Etc.
	BUS1	BUS2	BUS1	BUS2	* * * *
	Phase #1		Phase #2		



Enter pair of node names for each phase of line. "BUS1" field is always for the same end

This data card is distinguished by the key word "BRANCH" which is punched in columns 1-6 . The card is completely optional in that numerical values generated within "SEMLYEN SETUP" are unaffected by the presence or absence of it. The "BRANCH" card merely allows the user to specify pairs of 6-character node names which will be reproduced in columns 3-14 (fields "BUS1" and "BUS2" , each A6 format) of the EMTP branch cards which will be punched as output. Without such a "BRANCH" card, columns 3-14 of the branch cards which are to be punched as output will be blank.

2) "TOLERANCES" card (Point S3-b data)

TOLERANCES	field #1		field #2		field #3		field #4		field #5	
	Index	value	Index	value	Index	value	Index	value	Index	value
	I2	E11.0	I2	E11.0	I2	E11.0	I2	E11.0	I2	E11.0

The iterative procedures of "SEMLYEN SETUP" are controlled by 18 different near-zero tolerances, iteration limits, and the like. If no "TOLERANCES" card is supplied, built-in default values will b used, as per the following tabulation:

Index number	Variable name	Default value	Usage of variable within "SEMLYEN SETUP"
1	EPS	.005	Maximum least-square error
2	EPS1	.005	Maximum relative error of a_i or λ_i
3	FIT2Z	.1	"beginning" of time-step-response sequence
4	PIVTHR	1.E-5	Least squares minimum Jacobian pivot magnitude.
5	EPSRSE	.01	
6			
7	FT2EMX	1.E-4	Maximum steady-state error.
8	EPSEIG	1.E-7	Convergence tolerance for eigenvalue calculation
9	EPSPV2	1.E-16	Minimum size for squared pivot element, within inversion routine.
10	FMED	5000.	Frequency in Hz of the 2nd point of Y_o.
11	EPSYC	1.E-3	Maximum relative error, for the characteristic admittance fitting procedure.
12	EPSN	1.E-3	Maximum total error for the characteristic admittance fitting.
13	FFINP	1.0	Final value of time-domain fitted step response.
14	NFIT	10.	Maximum number of iterations for Δt selection.
15	NITER1	10.	Maximum number of iterations for steady-state fitting.
16	NITER	10.	Maximum number of iterations for least squares fitting.
17	NITERY	10.	Maximum number of iterations for characteristic admittance step-response fitting.
18	NIEIG	30.	Maximum number of iterations for the eigenvalue/vector calculation.

The "TOLERANCES" data card is characterized by this key-word text which is to be punched in columns 1-10 . By means of one or more such data cards, the user can re-define as many of the abov -tabulated param ters as he may desire. Note that there are five fields on each such data card, each with space for a 2-digit integer ("Index" ; I2 format) and a floating-point number ("value" ; E11.0 format). There are no restrictions as to ordering of the parameters which are to be altered, and not all fields need be filled (any blank fields are ignored).

As an example, suppose that the user wanted to allow as many as sixty it rations for the eigenvalue/vector calculation. He could punch "18" in columns 39-40 and "60." in columns 49-51 ---- which would correspond to the use of the third field on the data card.

3) Miscellaneous data card (Point S4 data)

The miscellaneous data card is the one mandatory card for each data cas within "SEMLYEN SETUP" . The format and meaning of parameters which are to be punched thereupon are as follows:

TEXT	NOO	NPOINT	NSS	KFIT	KPS	KYC	IOUT	[illegible]	IOTX	IOSS	IOFL	RHO	DIST	NPAN
A8	I5	I5	I2	I2	I2	I2	I2	I2	I6	I6	I6	E12.5	E12.5	I3

TEXT (1-8) ---- Eight characters of alphanumeric text, for which the following choices are possible:

a) If left blank, then the EMTP will expect a full "LINE CONSTANTS" or "CABLE CONSTANTS" data case to follow. Such a choice is mandatory for the first data case within "SEMLYEN SETUP" usage.

b) If punched with "NEW RHO " , then physical data for "LINE CONSTANTS" or "CABLE CONSTANTS" is assumed to be the same as was used for the preceding data case within "SEMLYEN SETUP" ; only the homogeneous earth resistivity "RHO" is to be different, as punched in the field of columns 49-60 ; In this case, Point S6 data is to be omitted (no "LINE CONSTANTS" or "CABLE CONSTANTS" data case is to follow).

c) If punched with "OLD DATA" , then line constants or cable constants of the preceding data case are to be re-used; only the transmission circuit length "DIST" (as punched in columns 61-72) is to be different.

NOO (9-13) ---- The number of points per travel time at the speed of light, for the propagation step response as found by inverse Fourier transformation (f_1 sequence).

This defines the basic time-axis spacing Δt which is to b_ used. See parameter "KFIT" below, also.

NPOINT —— number of time points for which the inverse fourier routine will calculate the response for fitting purposes.
(14-18)

NSS —— Flag which is used to indicate whether or not the transmission circuit phases are assumed to all be continuously transposed:
(19-20)

$$\begin{cases} 0 \Longrightarrow \text{Untransposed circuit} \\ 1 \Longrightarrow \text{Continuously-transposed circuit} \end{cases}$$

The untransposed circuit requires the iterative calculation of eigenvalues, while the continuously-transposed one does not, recall.

FIT —— There are several options controlled by two independent digits which are decoded from the field of width Two:
21-22)

N1 —— Digit which indicates how the characteristic admittance is to be fit. Leave blank or zero. for frequency-domain fitting (which is the usual case). A value of "1" will produce time-domain fitting, in theory.
(21)

N2-- Digit which indi$\overset{a}{\vee}$ctes the desired basis of the time-axis spacing Δt used for fitting of the propagations step response. A value of 0 will use Δt = travel time/NOO above.
(22)

A value of 1 will locate the 2/3 point of the propagation step response and size the Δt to put approximately 15% of NPOINT values between the toe and the 2/3 point.

A value of 2 will locate the 2/3 point and the 1/3 point
of the propagation step response and size the time step to
put approximately 5% of NPOINT values between the 1/3 and
2/3 points. Because of oscillations in the output of
inverse fourier routines, one or both of these points may
not be obtainable, requiring either a reduction in the
value of N2, or an increase in the number of frequency
points so as to increase the accuracy of the inverse
fourier routine.

KPS —— A flag which indicates whether or not fitting at the steady-state frequency is desired:
(23-24)

$$\begin{cases} 0 \text{ —— No fitting at the steady-state frequency} \\ 1 \text{ —— Attempt to fit the propagation step-response exactly at the steady-state frequency.} \end{cases}$$

2 ---- The same as for KPS = 1, except that if the iteration does not converge, the original (starting) fitting shall be reverted to.

KYC (25-26) ------ A parameter which indicates how the characteristic admittance is to be treated:

- 0 ⇒ For all modes, use fitted time-dependent characteristic admittance modeling;
- 1 ⇒ For all modes, use constant characteristic admittance modeling (at the steady-state frequency);
- 2 ⇒ Only the earth-return (zero-sequence) mode is to be treated as if KYC = 0 ; all line modes (if any) are to be treated as if KYC = 1 ;
- 3 ⇒ Like for KYC = 1 (constant characteristic admittance), only use the natural resonant frequency of the line in place of the steady-state frequency. This frequency is 0.5 / TAU , where "TAU" is the travel time of the line at the speed of light. Actually, the closest known frequency point to this resonant frequency will be used, for convenience.

Note that these options only use column 26 , really. Column 25 (the first of two possible digits) is used as an extra, independent flag, to be added after the above choice for column 26 has already been made. If column 25 is punched with "1" , there will be a printer plot of characteristic admittance vs. time, showing how the frequency-domain-fitted exponentials compare with an independent inverse Fourier transformation result.

IPUN (27-28) ------ Parameter which indicates whether or not the EMTP branch cards which are to be constructed are to be punched:

- 0 ------ Branch cards are to be outputted on both the line printer and the punch (LUNIT7);
- 1 ------ Punch only;
- 2 ------ Printer only.

Punched cards will appear on logical unit number "LUNIT7" , which is assigned within module "SYSDEP" of overlay number 1 if not equal to seven. Whether such output goes automatically to the punch, or to a disk file, will depend on the program setup (see Program Maintenance if there are questions).

IDOC (29-30) ------ Flag which indicates whether the branch cards that are to be outputted are to be preceded by descriptive comment cards. For this purpose, the data cards of "LINE CONSTANTS" or "CABLE CONSTANTS" are used, after conversion to comment cards ("C" in column number 1).

- 0 ⟹ no such comment cards will be outputted;
- 1 ⟹ yes, append these comment cards.

IOTX (31-36) ------ Parameter which controls the printout of intermediate results (e.g., eigenvalues and eigenvectors) which are computed at the frequency of the diagonalizing transformation (generally 5000 Hz or thereabouts).

- -1 ⟹ User is confused by octal numbers, and would prefer to punch "IOTX" , "IOSS" , and "IOFL" in binary. In this case, "IOSS" and "IOFL" fields (columns 37-48) are to be left blank, and three extra cards (Point S5 data) are to follow as extensions to the miscellaneous data card.
- 0 ⟹ No such intermediate printout is desired.
- K ⟹ Positive octal "K" will control the printout in question (at the transformation frequency) as documented in the explanation of Point S5 data.

IOSS (37-42) ------ Like "IOTX" above, only for the steady-state frequency (rather than for the transformation frequency). This field is ignored, if "IOTX" is equal to -1 .

IOFL (43-48) ------ Like "IOTX" above, only for ten discrete frequencies within the loop over geometrically-spaced frequencies. This field is ignored, if "IOTX" is equal to -1 .

RHO (49-60) ------ Resistivity of the homogeneous earth, in units of Ohm-meters . This data field is ignored unless "TEXT" of columns 1-8 is equal to either "NEW RHO " or "OLD DATA" .

DIST (61-72) ------ Length of the transmission circuit, in units of miles . This data field is ignored unless "TEXT" of columns 1-8 is equal to either "NEW RHO " or "OLD DATA" .

NPAN (73-75) ------ A special flag which is to be punched nonzero only if the user wants to experiment with an alternate inverse Fourier transformation which is based on the trapezoidal rule.

- 0 ⇒ No such trapezoidal-rule algorithm is desired;
- N ⇒ For positive "N", the trapezoidal rul will be used. "N" is the number of integration panels per cycle of the integrand, or per interval between successive line (cable) constants points ---- which ever is the smaller.

4) Extensions to miscellaneous data card (Point S5 data)

If and only if field "IOTX" of columns 31-36 of the miscellaneous data card is punched with the value -1, three extra cards are to immediately follow the miscellaneous data card as extensions to it. These three cards serve to define "IOTX", "IOSS", and "IOFL" ----- one variable per card, in this order. Binary is used, with up to twelve of the I4 fields of the following format being punched:

'I0??' Components (binary)											
1	2	3	4	5	6	7	8	9	10	11	12
I4	I4	I4	I4	I4	I4	I4	I4	I4	I4	I4	I4

Each of these component fields is to be assigned a binary digit (either zero or one). If zero (or blank), then the associated intermediate printout will not be generated; if unity, it will be. The following is a directory showing what printout is controlled by each bit:

Index number	Column number	Description of the printout which is being controlled by this component field
1	4	Approximate modal equivalent-Pi
2	8	Approximate modal equivalent-Pi
3	12	Approximate modal characteristic Z
4	16	Approximate modal Z, Y matrices
5	20	Approximate modal velocity and Attenuation
6	24	Phase-coordinate equivalent-Pi matrices
7	28	Modal equivalent-Pi matrices
8	32	Modal characteristic impedance

9	36	Exact modal Z and Y matrices
10	40	Exact modal velocity and attenuation
11	44	Exact transformation matrices
12	48	Matrices Z and Y in phase coordinates

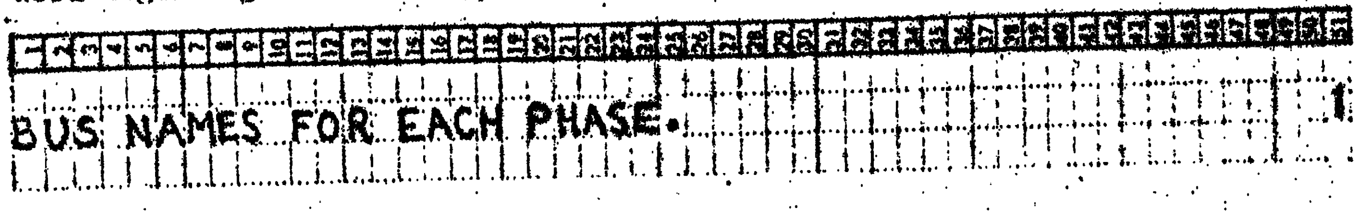
The relation between such binary specifications and the possible octal specifications of the miscellaneous data card is simple : separate the binary bits into groups of three, and then read as an octal number. For example,

1 0 1 0 0 1 1 1 0 1 0 0 (binary) = 101 001 110 100 = 5164 (octal)

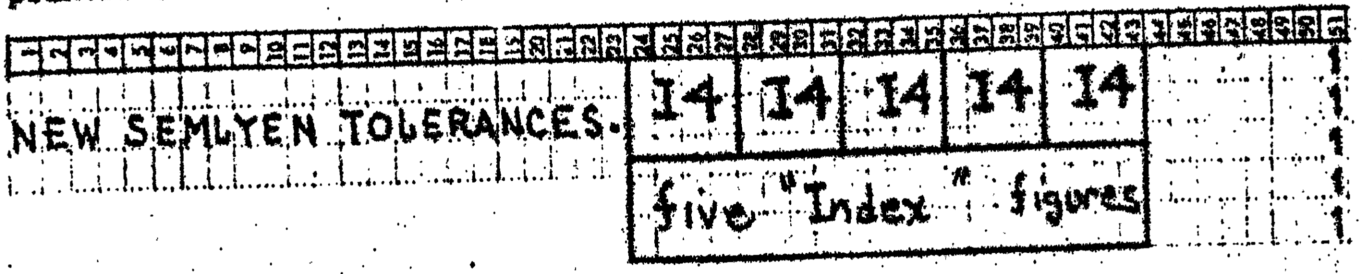
7.5-C Interpretation of input data cards

As with all EMTP data cards, an 80-column card-image listing is printed on the right of the page (as the card is read, within "CIMAGE"), and interpretation is provided in columns 1-50 (to the left of the column-51 separator character "1"). For the different data classes of Section 7.5-B , interpretations shall now be documented.

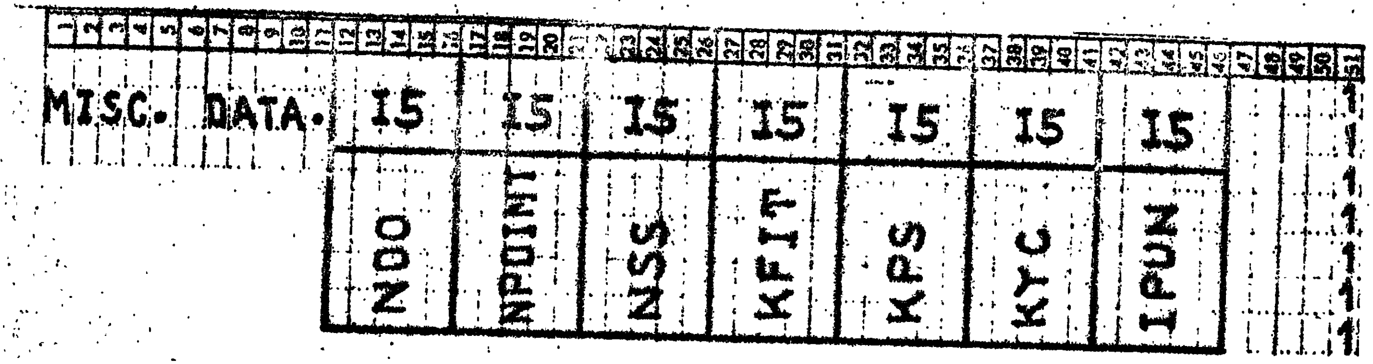
First, there is the "BRANCH" card (Point S3-a data, bearing this key word beginning in column 1), which is interpreted as follows:



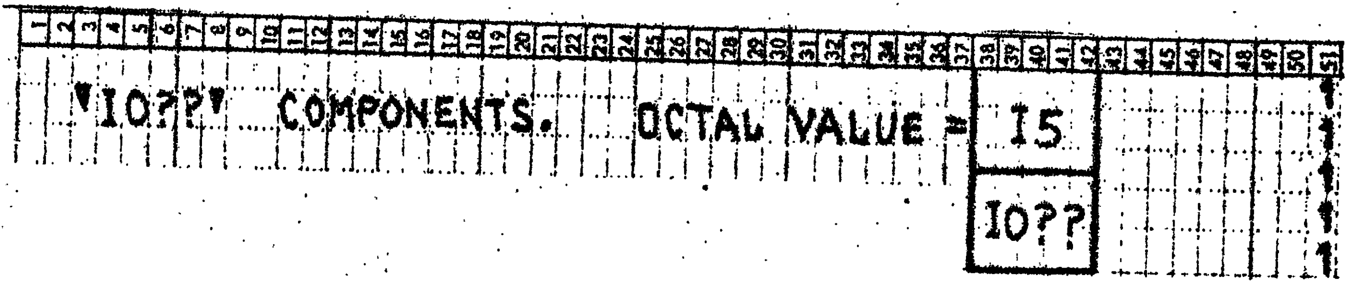
The "TOLERANCES" card (Point S3-b data, bearing this key word beginning in column 1) has interpretation which displays the five integer values (fields "Index") which are read from the card. These are in order, from left to right (e.g., the first integer is read from columns 13-14 and printed in columns 24-27 , etc.) :



Interpretation of the miscellaneous data card (Point S4 data) displays the first seven integer parameters which were read from the card, in order:



Finally, there are the three extensions to the miscellaneous data card (Point S5 data). Recall that such cards are used if the user wants to specify parameters "IOTX" , "IOSS" , and "IOFL" in binary rather than in octal ----- indicated by punching -1 in the "IOTX" field of columns 31-36 as a special flag. Well, interpretation of each of the three extension cards displays the resultant octal value, as internally constructed by the EMTP (from the user's 12I4 binary input digits). Note that an I5 field is used for convenience, although the result will never involve the digits "8" or "9" , and the printed number will never exceed 7777 . The "??" of "IO??" is merely a symbolic reference; "TX" will be used for the first extension card, "SS" for the second, and "FL" for the third:



653

7 5-D Illustrative line printer output for "SEMLYEN SETUP" data case

Printed output for an illustrative "SEMLYEN SETUP" EMTP data case shall now be displayed. The transmission circuit in question is a 3-phase overhead transmission line; there is no bundling, but there are two ground wires; and the length is 18.65 miles. A listing of the input data cards follows:

```
BEGIN NEW DATA CASE
C      EMTP TEST CASE NO. 100
SEMLYEN SETUP
BRANCH  SORCEALINE ASORCEBLINE BSORCECLINE C
                  60    30     2     1     7  7777  1637
LINE CONSTANTS
C      TEST 1 HORIZONTAL LINE 18.65 MILES LONG
   1.3159 .192     4              .658   -10.67     31.5      31.5
   2.3159 .192     4              .858     0.0      31.5      31.5
   3.3159 .192     4              .858    10.67     31.5      31.5
   0.5     3.46    4              .313    -5.33     40.5      40.5
   0.5     3.46    4              .313     5.33     40.5      40.5

   1000.     5000.                                  18.65
   1000.       60.                                  18.65
   1000.       60.                                  18.65              4 21
```

Printed output will begin with the interpretation of data cards through the "LINE CONSTANTS" card. Although for a different data case, the following is illustrative. Note use of the extensions to the miscellaneous data card (which is one reason for presenting this alternate sample):

```
[illegible] TRANSLATION PRODUCED BY THE BONNEVILLE POWER ADMINISTRATION, PORTLAND
[illegible] ANY PLOTS WITH THE SAME FIGURES.
[illegible] DATED NOVEMBER, 1977.
[illegible]
[illegible]
--------------------------------------------------------------------------------
[illegible]                                    [illegible] COLUMNS, CHARACTER
--------------------------------------------------------------------------------
[illegible]
[illegible]                                    LINE CONSTANTS
TRANSFER TO [illegible]
```

Next will come output from the "LINE CONSTANTS" overlay. Since such output is described in Section 7.4 , it shall not be further illustrated here.

After control returns from "LINE CONSTANTS" to "SEMLYEN SETUP", there will be output for the transformation-frequency parameters. For this case, the frequency is 5000 Hz (see next page):

```
CALCULATION OF TRANSFORMATION MATRICES.  CONTINUOUS TRANSPOSITION FLAG = 0

                                         FREQUENCY =     .5000E+04
                                         *************************

   IMPEDANCE MATRIX                         ADMITTANCE MATRIX
     (OHM/MILE)                               (MHO/MILE)

 .37503E+01
 .58433E+02                                 .0            .0            .0
                                            .41970E-03    -.69108E-04   -.27190E-04

 .29970E+01    .36736E+01
 .21313E+02    .77950E+02                                 .0            .0
                                                          .43011E-03    -.69108E-04

 .29933E+01    .29970E+01    .37503E+01
 .16357E+02    .21313E+02    .58433E+02                                 .0
                                                                        .41970E-03

   THE FOLLOWING VALUES ARE COMPUTED ON THE BASIS OF EXACT DIAGONALIZATION OF ZY MTX.

              MODE TO PHASE VOLTAGE                                  MODE TO PHASE CURRENT
              TRANSFORMATION MATRIX                                  TRANSFORMATION MATRIX

 1.00000    1.00000    -.42339             *
  .00000    -.00000     .00923             *    .39704     .50000    -.33768
                                           *    .00394    -.00000     .00099
  .84556    -.00000    1.00000             *
 -.31214     .00000     .00000             *    .38240    -.00000     .71487
                                           *   -.00760    -.00000     .00707
 1.00000   -1.00000    -.42339             *
  .00000    -.00000     .00923             *    .39704    -.50000    -.33768
                                           *    .00394     .00000     .00099

   MODE      ALPHA            BETA          ATTENUATION      VELOCITY
          (NEPER/MI)      (RADIANS/MI)       (DB/MI)        (MILE/SEC)

     1    .79053E-02      .19403E+00      .68664E-01      .16191E+06
     2    .99420E-03      .17821E+00      .86355E-02      .18497E+06
     3    .10691E-02      .16965E+00      .92857E-02      .18518E+06
```

Then will come output for the steady-state frequency (60 Hz):

```
                                         FREQUENCY =     .6000E+02
                                         *************************

   IMPEDANCE MATRIX                         ADMITTANCE MATRIX
     (OHM/MILE)                               (MHO/MILE)

 .29735E+00
 .14722E+01                                 .0            .0            .0
                                            .58364E-05    -.12929E-06   -.32638E-06

 .20593E+00    .30381E+00
 .75534E+00    .14613E+01                                 .0            .0
                                                          .52693E-05    -.12929E-06

 .20442E+00    .20593E+00    .29795E+00
 .67233E+00    .75534E+00    .14722E+01                                 .0
                                                                        .58364E-05

   THE FOLLOWING VALUES ARE COMPUTED ON THE BASIS OF EXACT DIAGONALIZATION OF ZY MTX.

              MODE TO PHASE VOLTAGE
              TRANSFORMATION MATRIX                                  MODE TO PHASE CURRENT
                                                                     TRANSFORMATION MATRIX
 1.44633    -.47718   -1.00000             *
  .36336    -.03266     .00000             *    .33601    -.34194    -.50000
                                           *   -.00098    -.00015    -.00000
 1.41574    1.00000     .00000             *
  .34343     .00000     .00000             *    .32145     .67367    -.00000
                                           *    .70086    -.00196    -.00000
 1.43630    -.47718    1.00000             *
 -.34288    -.03266     .00000             *    .33601    -.34194     .50000
                                           *   -.00098    -.00015     .00000

   MODE      ALPHA            BETA          ATTENUATION      VELOCITY
          (NEPER/MI)      (RADIANS/MI)       (DB/MI)        (MILE/SEC)

     1    .46843E-03      .36913E-02      .40687E-02      .10215E+06
     2    .28668E-03      .20712E-02      .24901E-02      .18114E+06
     3    .25320E-03      .20451E-02      .21993E-02      .18079E+06

      DISTRIBUTED SERIES         DISTRIBUTED SHUNT          CHARACTERISTIC            EQUIVALENT PI SERIES       HALF EQUIV PI SHUNT
      IMPEDANCE(OHM/MILE)        ADMITTANCE(MHO/MILE)       IMPEDANCE(OHMS)           IMPEDANCE(OHMS)            ADMITTANCE(MH
MODE   REAL        IMAG          REAL        IMAG           REAL        IMAG          REAL        IMAG           REAL        IMA

  1   [illegible]  [illegible]   .0     .11484E-04   .29760E+03  -.36447E+02   .52641E+01  .17943E+02   .56994E-04  [illegible]
  2   [illegible]  [illegible]   .0     .59972E-05   .73126E+03  -.12234E+02   .29451E+01  .77467E+01   .29412E-04  [illegible]
  3   [illegible]  [illegible]   .0     .18726E-04   .49452E+03  -.13150E+02   .16313E+01  .74512E+01   .93369E-04  [illegible]
```

```
     PI EQUIVALENT SERIES                       HALF PI EQUIV SHUNT
   IMPEDANCE MATRIX(OHMS)                     ADMITTANCE MATRIX(MHOS)

 .74364E+01                                .21959E-08   .[illegible]-09   .63266E-09
 .27438E+02                                .46[illegible]E-04  -.7[illegible]E-04  -.30415E-05

 .39464E+01    .77297E+01                               .2[illegible]E-11   .37[illegible]E-09
 .14051E+02    .27338E+02                               .4[illegible]E-04  -.77[illegible]E-05

 .38326E+01    .39464E+01    .74364E+01                                .21[illegible]E-08
 .12534E+02    .14061E+02    .27438E+02                                .46[illegible]E-04

   THE FOLLOWING VALUES ARE COMPUTED BY USE OF CONSTANT TRANSFORMATION MATRICES.

               ALPHA             BETA          ATTENUATION        VELOCITY
   MODE     (NEPER/MI)      (RADIANS/MI)        (DB/MI)        (MILE/SEC)

     1      .46077E-03       .33599E-02       .4[illegible]E-02     .1122[illegible]E+06
     2      .24960E-03       .2[illegible]E-02       .21[illegible]E-0[illegible]     .18[illegible]E+06
     3      .26589E-03       .2[illegible]E-02       .2431[illegible]E-0[illegible]     .1[illegible]E+06

     DISTRIBUTED SERIES      DISTRIBUTED SHUNT          CHARACTERISTIC          EQUIVALENT PI SERIES   HALF EQUIV PI SHUNT
   IMPEDANCE(OHM/MILE)    ADMITTANCE(MHO/MILE)        IMPEDANCE(OHMS)          IMPEDANCE(OHMS)      ADMITTANCE(MHOS)
 JE    REAL       IMAG       REAL       IMAG           REAL        IMAG          REAL        IMAG        REAL        IMAG

 1  .24167E+00 .15672E+01   .0      .10996E-04   .38[illegible]E+03 -.41[illegible]E+02   .52445E+01  .18773E+02  .92064E-08  .13257E-
 2  .99[illegible]E-01 .3[illegible]E+00   .0      .10720E-04   .10[illegible]E+03 -.2[illegible]E+02   .15[illegible]E+01  .74518E+01  .33065E-08  .4[illegible]E-
 3  .14[illegible]E+0[illegible] .5[illegible]E+00   .0      .83625E-05   .29[illegible]E+03 -.34[illegible]E+02   .24655E+01  .95924E+01  .27038E-08  .77990E-0

     PI EQUIVALENT SERIES                       HALF PI EQUIV SHUNT
   IMPEDANCE MATRIX(OHMS)                     ADMITTANCE MATRIX(MHOS)

 .75243E+01                                .22334E-08   .3422[illegible]E-09   .77952E-09
 .27923E+02                                .46975E-04  -.77314E-05  -.30394E-05

 .3[illegible]E+01    .73509E+01                               .22237E-08   .34222E-09
 .1373[illegible]E+02    .26292E+02                               .47145E-04  -.77315E-05

 .3921[illegible]E+01    .38210E+01    .75243E+01                                .22338E-08
 .13[illegible]E+02    .13729E+02    .27923E+02                                .46975E-04
```

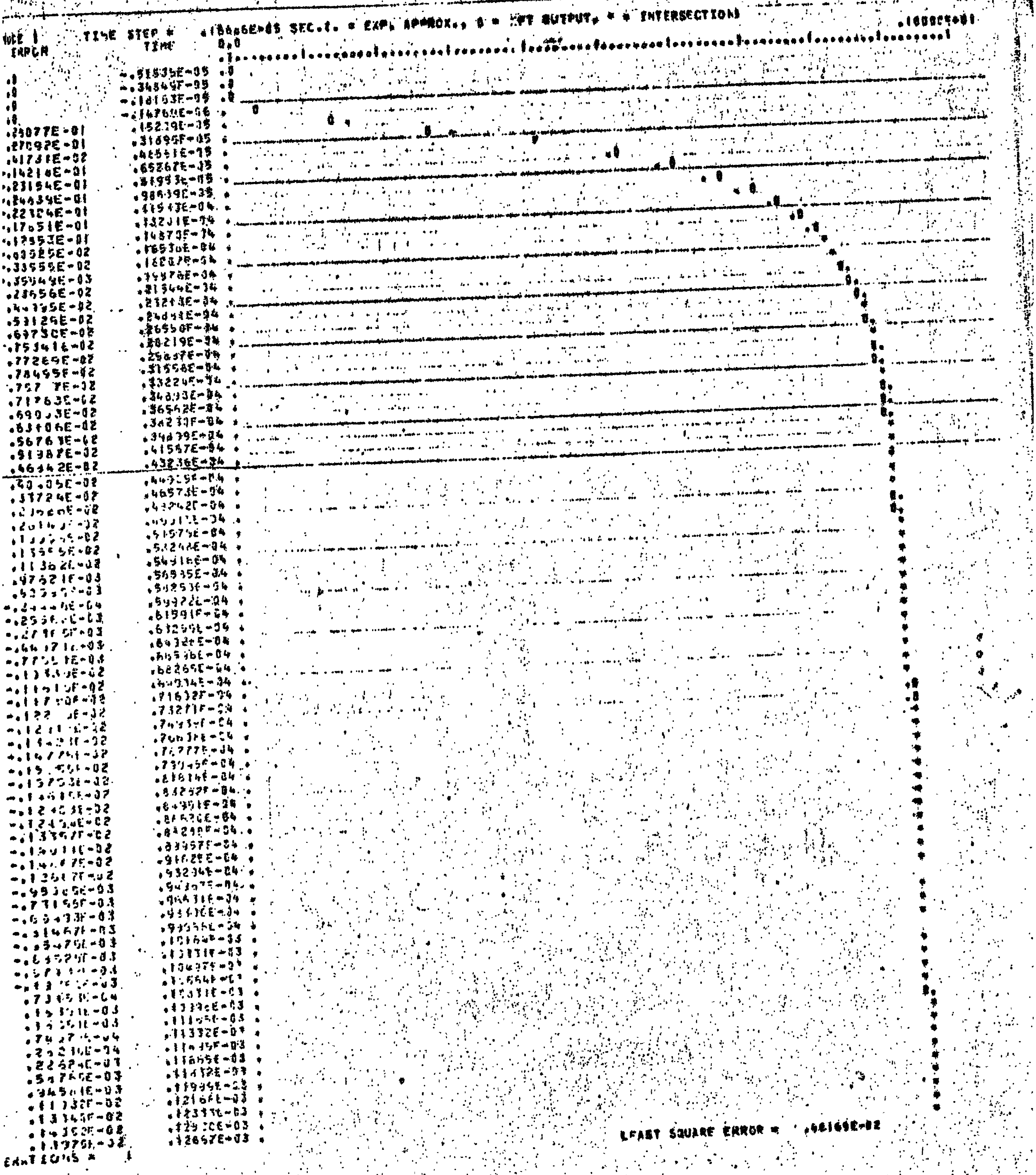
Finally will come similar outputs for ten representative frequencies within the looping over logarithmically-spaced frequencies. The first of the ten appears as follows:

```
NO.FREQ =  65     FIRST FREQUENCY =   60.00000     LAST FREQUENCY =   630000.0    GEO.RATIO = 1.116
       TRAVEL TIME =   .10012E-03     APPROX. NO. TIME STEPS PER TRAVEL TIME =  60


                                           FREQUENCY =        .1293E+03
                                           *************************


     IMPEDANCE MATRIX                            ADMITTANCE MATRIX
       (OHM/MILE)                                  (MHO/MILE)

 .74291E+00                                .0           .0            .0
 .28[illegible]E+01                                .10851E-04  -.17867E-03   -.70316E-06

 .56315E+00    .77749E+00                              .0            .0
 .13376E+01    .26657E+01                              .11352E-04   -.17867E-05

 .56434E+00    .56315E+00    .74291E+00                                .0
 .116[illegible]E+01    .13375E+01    .28909E+01                                .10851E-04

   THE FOLLOWING VALUES ARE COMPUTED ON THE BASIS OF EXACT DIAGONALIZATION OF ZY MTX.

                  MODE TO PHASE VOLTAGE                                        MODE TO PHASE CURRENT
                 TRANSFORMATION MATRIX                                        TRANSFORMATION MATRIX

 1.00000   -.47735   -1.00000                                  *     .33675   -.34199   -.50890
  .00000    .00396     .00000                                  *     .00145    .00022   -.00000
                                                               *
 1.31555   1.00000    .00000                                   *     .32151    .67350   -.00002
 -.00505    .00000    .00000                                   *    -.00127    .00292   -.00000
                                                               *
 1.00000   -.47735   1.00000                                   *     .33675   -.34199    .50000
 -.00000    .00396    .00000                                   *     .00146    .00022    .00000

               ALPHA             BETA          ATTENUATION        VELOCITY
   MODE     (NEPER/MI)      (RADIANS/MI)        (DB/MI)        (MILE/SEC)

     1      .1142[illegible]E-02       .82[illegible]E-02       .97[illegible]E-02     .12[illegible]E+06
     2      .2936[illegible]E-03       .445[illegible]E-02       .255[illegible]E-02     .1[illegible]E+06
     3      .2[illegible]E-03       .44673E-02       .22[illegible]E-02     .1818[illegible]E+06
```

```
      DISTRIBUTED SERIES      DISTRIBUTED SHUNT       CHARACTERISTIC         EQUIVALENT PI SERIES    HALF EQUIV PI SHUNT
      IMPEDANCE(OHMS/MILE)    ADMITTANCE(MHO/MILE)    IMPEDANCE(OHMS)        IMPEDANCE(OHMS)          ADMITTANCE(MHOS)
MODE   REAL       IMAG        REAL        IMAG        REAL       IMAG        REAL       IMAG          REAL       IMAG

  1   .61255E+00 .17932E+01  .0         .24745F-04  .27371E+03 -.45189E+02
  2   .12536E+00 .10177E+01  .0         .19388E-04  .22956E+03 -.16537E+02
  3   .99031E-01 .66070E+00  .0         .23106F-04  .19331E+03 -.11044E+02

     THE FOLLOWING VALUES ARE COMPUTED BY USE OF CONSTANT TRANSFORMATION MATRICES.

             ALPHA            BETA            ATTENUATION       VELOCITY
   MODE    (NEPER/MI)      (RADIANS/MI)         (DB/MI)        (MILE/SEC)

     1     .11264E-02      .67960E-02         .37637E-07       .120  E+06
     2     .25814E-03      .44670E-02         .22241E-02       .181  E+06
     3     .25875E-03      .44547E-02         .25775E-07       .14 31E+06

      DISTRIBUTED SERIES      DISTRIBUTED SHUNT       CHARACTERISTIC         EQUIVALENT PI SERIES    HALF EQUIV PI SHUNT
      IMPEDANCE(OHMS/MILE)    ADMITTANCE(MHO/MILE)    IMPEDANCE(OHMS)        IMPEDANCE(OHMS)          ADMITTANCE(MHOS)
MODE   EAL        IMAG        REAL        IMAG        REAL       IMAG        REAL       IMAG          REAL       IMAG

  1   .54267E+03 .18744F+01  .0         .23449E-06  .29528E+03 -.47449E+02
  2   .93031E-01 .66073E+00  .0         .23106E-04  .19331E+03 -.11085E+02
  3   .14676E+00 .10587E+01  .0         .18016E-04  .24727E+03 -.16471E+02
```

Next will come output which shows how the exponentials are fitted to the propagation step responses, for each of the three modes. The first of such outputs will be for mode number one, which is the zero-sequence mode Note that the printer plot shows graphically the approximation which is involved in use of the exponentials. Symbols on the plot are "O" for the exact curve (result of inverse Fourier transformation), "." for the exponential locus, and "*" is used whenever the preceding two lie one on top of the other.

```
          FITTING OF THE PROPAGATION STEP RESPONSE FOR MODE  1


NO.ITER.        AMPL.            X(1)             X(2)             X(3)             ERROR

   1        [illegible]      .10482E+02       .39621E+00       .68142E-01       .38008E-01
   1        [illegible]      .[illegible]E+02 .39621E+00       .68142E-01       .13818E-01
   1        [illegible]      .12218E+02       .39621E+00       .68142E-01       .46185E-02
   1        [illegible]      .13468E+02       .39621E+00       .68142E-01       .59655E-02
   1        .47[illegible]E+00 .14954E+02     .39621E+00       .68142E-01       .14784E-01
   1        .47331E+00       .16522E+02       .39621E+00       .68142E-01       .28994E-01
   1        .47321E+00       .17390E+02       .39621E+00       .68142E-01       .46742E-01
   1        [illegible]      .19159E+02       .39621E+00       .68142E-01       .67189E-01
   1        [illegible]      .11227E+02       .39621E+00       .68142E-01       .39407E-01
   1        [illegible]      .20295E+02       .39621E+00       .68142E-01       .11278E+00
   1        [illegible]      .12813E+02       .39621E+00       .68142E-01       .46169E-02
ITERATIONS TO ADJUST FITTING AT 60HZ
             AMPL 1           AMPL 2           TIME CONST        ERROR AT 60HZ

   1        .49291E+00       .11739E+00       .58116F-03        .31117E-01
   2        [illegible]      .13217E+00       .52676F-03        .39368E-01
   3        [illegible]      .97449E-01       .55412E-03        .29335E-01
   4        [illegible]      .92939E-01       .58327E-03        .39283E-01
   5        .911[illegible]E+00 .88652E-01    .61406E-03        .29231F-01
   6        .91540E+00       .84501F-01       .64661E-03        .29180F-01
   7        .91320E+00       .83738E-01       .68075F-03        .29131E-01
   8        .92275E+00       .77257E-01       .71629E-03        .29083E-01
   9        .92603E+00       .73972E-01       .75299E-03        .29037E-01
60HZ FITTING TOLLERANCE NOT ACHIEVED.  ERROR =      .339936F-01
WARNING---PROGRAM CAN NOT ADJUST PROPAGATION STEP RESPONSE TO FIT EXACTLY AT STEADY STATE FREQUENCY.
         INITIAL FITTING ASSUMED.

                         FIRST AMPLITUDE          =      .887885F+00
                         FIRST TIME CONSTANT      =      .781368F-05
                         SECOND AMPLITUDE         =      .112195F+00
                         SECOND TIME CONSTANT     =      .252684E-03
                         DELAY                    =      .106938E-03
```



```
UCE I      TIME STEP *    .16666E-05 SEC., . = EXP. APPROX., 0 = EMT OUTPUT, * = INTERSECTION                  .10000E+01
 ERROR          TIME        0.0
                            .I........I.........I.........I.........I.........I.........I.........I.........I.........I
                -.51535E-05 .0
.0              -.34849E-05 .0
.0              -.18153E-05 .0
.0              -.14760E-06 .   0
.0               .15219E-05 .
.23077E-01       .31695E-05 .
.27092E-01       .48551E-05 .
.41731E-02       .65267E-05 .
-.14216E-01      .81993E-05 .
-.23154E-01      .98639E-05 .
-.24634E-01      .11541E-04 .
-.22124E-01      .13211E-04 .
-.17051E-01      .14873E-04 .
-.12553E-01      .16530E-04 .
-.03525E-02      .18207E-04 .
-.33555E-02      .19978E-04 .
-.35949E-03      .21544E-04 .
.23556E-02       .23213E-04 .
.4[illegible]E-02       .24891E-04 .
.53126E-02       .26550E-04 .
.63730E-02       .28219E-04 .
.75341E-02       .29887E-04 .
.77269E-02       .31556E-04 .
.78495E-02       .33224E-04 .
.757[illegible]7E-02       .34893E-04 .
.71763E-02       .36562E-04 .
.690[illegible]3E-02       .38231F-04 .
.63106E-02       .39899E-04 .
.56763E-02       .41567E-04 .
.51387E-02       .43236E-04 .
.46442E-02       .44905E-04 .
.40[illegible]05E-02       .46573E-04 .
.37724E-02       .48242E-04 .
[illegible]      .49911E-04 .
[illegible]      .51579E-04 .
[illegible]      .53248E-04 .
.1[illegible]E-02       .54916E-04 .
.11362E-02       .56585E-04 .
.97621E-03       .58253E-04 .
.5[illegible]E-03       .59922E-04 .
-.2[illegible]E-04      .61591F-04 .
-.25[illegible]E-03      .63259E-04 .
-.27[illegible]E-03      .64928E-04 .
-.44[illegible]E-03      .66596E-04 .
-.77[illegible]E-03      .68265E-04 .
-.1[illegible]E-02      .69934E-04 .
-.11[illegible]E-02      .71602E-04 .
-.11[illegible]E-02      .73271F-04 .
-.122[illegible]E-02      .74939E-04 .
-.12[illegible]E-02      .76608E-04 .
-.1[illegible]E-02      .78277E-04 .
-.14[illegible]E-02      .79945E-04 .
-.15[illegible]E-02      .81614E-04 .
-.137[illegible]E-02      .83282E-04 .
-.1[illegible]E-02      .84951E-04 .
-.12[illegible]E-02      .86620E-04 .
-.124[illegible]E-02      .88288E-04 .
-.13[illegible]E-02      .89957E-04 .
-.1[illegible]E-02      .91626E-04 .
-.1[illegible]E-02      .93294E-04 .
-.12[illegible]E-02      .94963E-04 .
-.99[illegible]E-03      .96631E-04 .
-.771[illegible]E-03      .98300E-04 .
-.6[illegible]E-03      .99969E-04 .
-.314[illegible]E-03      .10164E-03 .
-.[illegible]E-03      .10331E-03 .
-.6[illegible]E-03      .10497E-03 .
-.5[illegible]E-03      .10664E-03 .
-.1[illegible]E-03      .10831E-03 .
.73[illegible]E-04       .10998E-03 .
.1[illegible]E-03       .11165E-03 .
.1[illegible]E-03       .11332E-03 .
.7[illegible]E-04       .11499E-03 .
.2[illegible]E-04       .11665E-03 .
.22[illegible]E-03       .11832E-03 .
.5[illegible]E-03       .11999E-03 .
.[illegible]E-03       .12166E-03 .
.11[illegible]E-02       .12333E-03 .
.13[illegible]E-02       .12500E-03 .
.1[illegible]E-02       .12667E-03 .
.1[illegible]E-02
[illegible]TIONS =    1                                                        LEAST SQUARE ERROR =   .46169E-02
```

Finally, the printout will end with information about the admittance fitting, and a listing of the EMTP branch cards which are to be punched. This is shown on the following page:

```
      FITTING FOR CHARACTERISTIC ADMITTANCE MODE NO  1

      NO. OF ITERATIONS =   3

 FREQUENCY =      60.     IMPULSE =   .32124E-02    .44058F-03    ERROR =  -.27942E-14   -.13898E-11
 FREQUENCY =  600000.     IMPULSE =   .51129E-02    .13967E-03    ERROR =   .0           .17347E-17
      AMPLITUDES =   .32722E-02        .18907E-02
      TIME CONST =   .14452E-01        .36002E-05
      INITIAL VALUE OF CHARACTERISTIC ADMITTANCE =    .51229E-02

      FITTING FOR CHARACTERISTIC ADMITTANCE MODE NO  2

      NO. OF ITERATIONS =   2

 FREQUENCY =      60.     IMPULSE =   .50715E-02    .50463F-03    ERROR =  -.12714E-11   -.36051E-09
 FREQUENCY =  600000.     IMPULSE =   .52792E-02    .58254E-05    ERROR =   .66736E-14    .10842F-18
      AMPLITUDES =   .51435E-02        .13597E-03
      TIME CONST =   .22262E-01        .82457E-05
      INITIAL VALUE OF CHARACTERISTIC ADMITTANCE =    .52794E-02

      FITTING FOR CHARACTERISTIC ADMITTANCE MODE NO  3

      NO. OF ITERATIONS =   3

 FREQUENCY =      60.     IMPULSE =   .39376E-02    .54203F-03    ERROR =  -.43081E-13   -.54357E-11
 FREQUENCY =  600000.     IMPULSE =   .41296E-02    .22695E-09    ERROR =   .43362E-18    .13553E-19
      AMPLITUDES =   .40121E-02        .11753E-03
      TIME CONST =   .19293F-01        .14075E-04
      INITIAL VALUE OF CHARACTERISTIC ADMITTANCE =    .41296E-02


                          SEQUENTIAL LIST OF PUNCHED OUTPUT.
                          ==================================
 C LENGTH=   138.0MILES, RHO=     27.0, SS FREQ=   60.00, NSS=1, KFIT=0, KPS=2, KYC=0
 C    1.3636 .05215  4             1.602   -20.75    50.      50.
 C    1.3636 .05215  4             1.602   -19.25    50.      50.
 C    2.3636 .05215  4             1.602   - 0.75    77.5     77.5
 C    2.3636 .05215  4             1.602     0.75    77.5     77.5
 C    3.3636 .05215  4             1.602    19.25    50.      50.
 C    3.3636 .05215  4             1.602    20.75    50.      50.
 C    0.5    2.61    4             0.386   -12.9     98.5     98.5
 C    0.5    2.61    4             0.386    12.9     98.5     98.5
 C
 C  27.          60.00             1                   138.
 C  27.          60.00             1                   138.          4 13
 C
 -1JDA    LMA                 0.22280E-02 0.77327E-03                 1   1   2   2    3
    0.67519495E+02 0.22868008E+03 0.00000000E+00 0.62996692E-03 0.60000000E+02
    0.00000E+00 0.12084E+05 0.88084E+00 0.00000E+00 0.39354E+03 0.11916E+00
    0.00000E+00 0.54169E+02-0.16419E-02 0.00000E+00 0.16009E+06-0.58610E-03
 -1JDB    LMB                 0.35995E-02 0.74081E-03                 2   2   2   2    3
    0.40944358E+01 0.80845416E+02 0.00000000E+00 0.10069636E-02 0.60000000E+02
    0.00000E+00 0.15539E+06 0.99245E+00 0.00000E+00 0.46338E+03 0.75457E-02
    0.00000E+00 0.99262E+01-0.35281E-02 0.00000E+00 0.20367E+06-0.71374E-04
 -1JDC    LMC                 0.35995E-02 0.74081E-03                 3   3   2   2    3
    0.40944358E+01 0.80845416E+02 0.00000000E+00 0.10069636E-02 0.60000000E+02
    0.00000E+00 0.15539E+06 0.99245E+00 0.00000E+00 0.46338E+03 0.75457E-02
    0.00000E+00 0.99252E+01-0.35281E-02 0.00000E+00 0.20367E+06-0.71374E-04
    0.57735E+00 0.00000E+00 0.70711E+00 0.00000E+00 0.40825E+00 0.00000E+00
    0.57735E+00 0.00000E+00-0.70711E+00 0.00000E+00 0.40825E+00 0.00000E+00
    0.57735E+00 0.00000E+00 0.00000E+00 0.00000E+00-0.81650E+00 0.00000E+00
    0.57735E+00 0.00000E+00 0.70711E+00 0.00000E+00 0.40825E+00 0.00000E+00
    0.57735E+00 0.00000E+00-0.70711E+00 0.00000E+00 0.40825E+00 0.00000E+00
    0.57735E+00 0.00000E+00 0.00000E+00 0.00000E+00-0.81650E+00 0.00000E+00


BLANK CARD TERMINATING   "SEMLYEN SETUP" .          1
```

Historical Perspective: All of the preceding material of Section 7.5 was written during the summer or fall of 1977, for original release in the November 1977 EMTP User's Manual (which then was the Reference Manual for "M21." program versions). But even for "M21." versions, it was slightly dated, as Tom Varilek and associates of Minnesota Power & Light discovered in August of 1978. Minor adjustments were continuously made over a period of a year or two, so that details of the output would not agree exactly. Then in the fall of 1979, BPA renounced all support for the "SEMLYEN SETUP" overlay, and developed the all-new "HAUER SETUP" feature of Section 7.8 . Russ Brierley of Ontario Hydro still uses "SEMLYEN SETUP", however, so all questions related to it are referred to him (see Section 0.5c for his address and telephone number).

7.6 "AMETANI SETUP" Routine

By means of the special request word "AMETANI SETUP" , an EMTP user gains access to the supporting routine which bears this same name, as per the explanation of Section 7. . The principal function of this code is to punch the branch cards which are needed for the representation of a transmission circuit using Ametani Linear Convolution modeling. See Section 1.27 and Section 1.27b .

The basic, original "AMETANI SETUP" code came from Professor Akihiro Ametani of Doshisha University, Kyoto, Japan; it was developed under contract with BPA during the summer of 1976 (which Aki spent in Portland). Tsu-huei (Dr. Tsu-huei Liu of BPA) made it machine translatable (sort of), and integrated it into the EMTP. Also, she removed the built-in line constants calculation, replacing it with a connection to the EMTP "LINE CONSTANTS" or "CABLE CONSTANTS" supporting routines.

The structure of a data case for "AMETANI SETUP" is as follows:

1. First comes a "BEGIN NEW DATA CASE" card (actually optional, as per Section 1.0a).
2. Next comes an "AMETANI SETUP" card, which serves to transfer control to the overlay in question (UTPF overlay number 46).
3. Next comes a complete "LINE CONSTANTS" or "CABLE CONSTANTS" data case (minus the "BEGIN NEW DATA CASE" card), as described in Section 7.4 or Section 7.7 . Exactly one frequency card must be used; the frequency which is to be punched thereupon is the steady-state frequency of interest (the frequency of the EMTP phasor solution, if any).

PROBLEM! PROBLEM! PROBLEM! PROBLEM! PROBLEM! PROBLEM! PROBLEM!

Page 231 (the beginning of which is seen above) was the sum total of Section 7.6 in the User's Manual dated November, 1977 ("M21." program versions). But to be used effectively for a wide range of power system problems, much more explanation is required. This was never written, however. Then during the summer of 1978, Bob Eifrig completely recoded the Semlyen/Ametani solution code (which shared the same EMTP tables), allowing an arbitrary number of linear segments for the piecewise-linear representation of propagation and admittance responses. But this new solution code has never been debugged (we at BPA have had our hands full just struggling with the Semlyen half of the modeling capability). Further, the old "AMETANI SETUP" code has not been modified so as to interface properly with the new format requirements of Bob Eifrig for EMTP branch cards. So, not only is "AMETANI SETUP" still limited to five straight-line segments, but even that output no longer can be directly used with the new EMTP for simulation purposes. There is no documentation at all of Bob Eifrig's new Ametani solution code (note that Section 1.27 mentions only exponentials, not straight-line segments). Whether Aki or some other party will complete the development at a later date is quite uncertain at this time (May, 1980). At this point, all we can do is say that Ametani convolution is no longer working, that Aki has been victimized by incomplete development further notice all but the most knowledgable

7.7 "CABLE CONSTANTS" Supporting Routine

7.7.1 Introduction and Background

By means of the special request word "CABLE CONSTANTS" , an EMTP us r gains access to the supporting routine which bears this same name, as per the explanation of Section 7. . The principal function of this code is to calculate the resistance, inductance, and capacitance matrices which correspond to an arbitrary configuration of single-core (SC) coaxial cables. A pipe-type configuration (where the aforementioned SC coaxial cables are all enclosed in a conducting pipe) is also allowed. Line constants for conventional overhead transmission lines can also be calculated using "CABLE CONSTANTS" ; this calculation is completely independent of the "LINE CONSTANTS" routine of Section 7.4 .

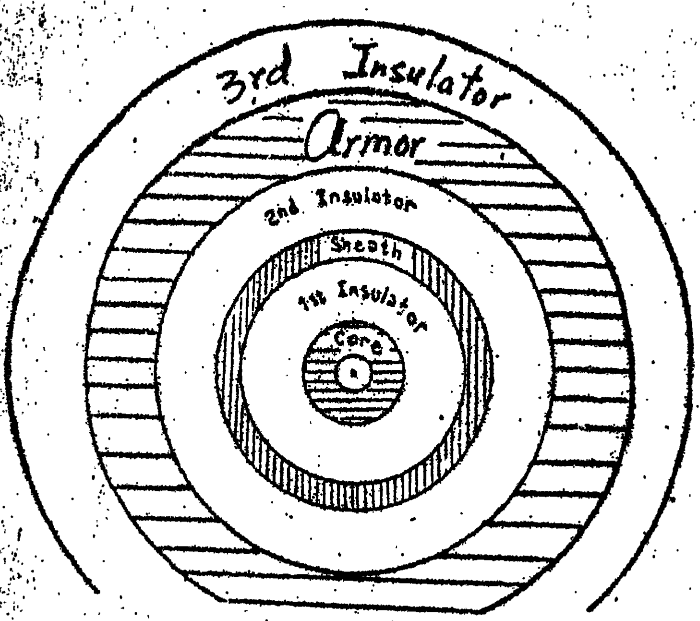


Fig. 1. Cross-section of most general SC coaxial cable geometry.

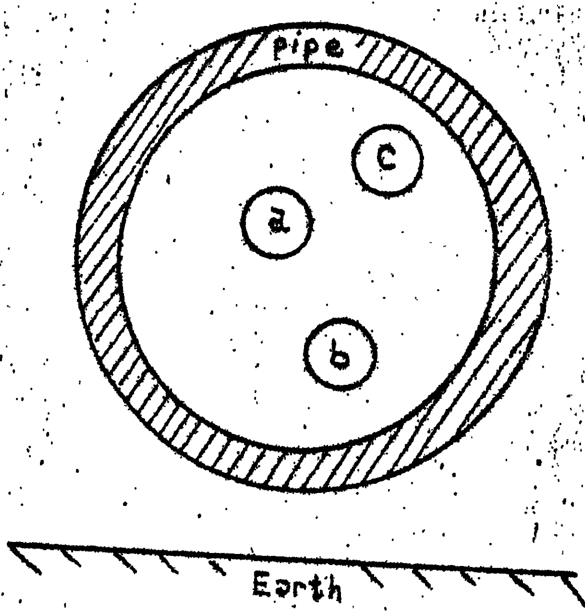


Fig. 2. Illustrative cross-section of overhead pipe-type cabl system which contains three SC coaxial cables.

History of the EMTP "CABLE CONSTANTS" routine might be briefly summarized. As described in Section V-B (page MPFT-35) of the Vol. IV EMTP memorandum dated March 27, 1976 (see Reference 8), Prof. Akihiro Ametani of Doshisha University in Kyoto, Japan was retained by BPA to work on the calculation of cable constants, among other things. This work, performed in the Spring and Summer of 1976, led to what is today the EMTP "CABLE CONSTANTS" feature. Pipe-type capability was added a year later, also under contract. Aki had written and tested a separate, self-contained program, which Tsu-huei (Dr. Tsu-huei Liu of BPA) then integrated into the EMTP, making it machine translatable (sort of) and otherwise compatible. Further details of this implementation work are covered in Reference 8, Vol. VII, July 14, 1977.

There are two important restrictions or limitations t the "CABLE CONSTANTS" routine, as of September, 1977:

Restriction 1 : The "CABLE CONSTANTS" code is fixed-dimension. A maximum of ten cores and sheaths (ten SC coaxial cables) is presently provided for; matrices are limited to 20 rows and columns.

Restriction 2 : The code of "CABLE CONSTANTS" makes heavy use of FORTRAN COMPLEX variables. For some computers, precision might conceivably be a problem (it is not clear, as of September, 1977) For example, Univac, Honeywell, and G.E. Mark III are believed to be limited to 36 bits of floating-point precision; there is no complex double-precision arithmetic on these systems, apparently.

7.7.2 General Structure of "CABLE CONSTANTS" Data Cards.

The structure of an EMTP data case which uses "CABLE CONSTANTS" will depend upon which of the following three classes it falls into:

Class A : System of SC coaxial cables without any enclosing pipe
Class B : System of SC coaxial cables within an enclosing pipe
Class C : System of conventional overhead conductors

Class A Data Structure

Consider the case of a system of SC coaxial cables, but no conducting pipe to enclose it. An EMTP data case which uses "CABLE CONSTANTS" for this class of problem then will have input data cards ordered as follows:

A1. First comes a "BEGIN NEW DATA CASE" card (actually optional, as per Section 1.0a).

A2. Next comes a "CABLE CONSTANTS" card, which serves to transfer control to the overlay in question (UTPF overlay number 47).

A3. Next comes a miscellaneous data card.

A4. Next comes one (or possibly more) card upon which is punched the number of conductors which make up each SC coaxial cable of the system. One card will suffice for a system of up to sixteen cables; two cards are required for 17-32 cables, etc.

A5. Next come two (or possibly three) cards of geometrical and physical data for each SC coaxial cable in the system. E.g., for three SC coaxial cables, a maximum of nine cards would be required.

A6. Next comes one (or possibly more) card which gives the horizontal and vertical location of the centers of all SC coaxial cables in the system. A single card will handle up to four SC coaxial cables; two cards are required for 5-8 , etc.

A7. Next comes a frequency card, which specifies a new earth resistivity and frequency (or range of frequencies) for which cable constants are to be calculated.

A8. Only if the stratified earth modeling is being used for an overhead cable system, two additional cards are required, to give all parameters of this more complex earth model. If the earth is instead modeled as homogeneous, no such cards exist.

A9. Repeat the data of Point A7 and Point A8 for as many different discrete frequencies or frequency ranges as may be desired. Signal the end of such data by means of a blank card.

A10. Repeat the data of Points A3 – A9 as often as may be desired. Each such grouping is a separate, distinct, independent data case within the "CABLE CONSTANTS" routine. Signal the end of such data by means of a blank card, which serves to transfer control back to the regular EMTP solution-mode, ready to read in a new EMTP data case.

A11 If the user wants to shut off the EMTP at this point (rather than execute a following EMTP data case), he should simply add a "BEGIN NEW DATA CASE" card at this point, followed by a blank card. This is as per Section 1.0b .

Class B Data Structure

Consider the case of a system of SC coaxial cables which are all enclosed by a conducting pipe. An EMTP data case which uses "CABLE CONSTANTS" for this class of problem will then have input data cards ordered as follows:

B1. First comes a "BEGIN NEW DATA CASE" card (actually optional, as per Section 1.0a) .

B2. Next comes a "CABLE CONSTANTS" card, which serves to transfer control to the overlay in question (UTPF overlay number 47).

B3. Next comes a miscellaneous data card.

B4. Next will come one card which gives parameters of the pipe.

B5 Next will come one (or possibly more) card which specifies the location of each SC coaxial cable within the pipe. One card will suffice for up to 4 SC coaxial cables, two will be required for 5–8 SC coaxial cables, etc.

B6. Next comes one (or possibly more) card upon which is punched the number of conductors which make up each SC coaxial cable of the system. One card will suffice for a system of up to sixteen cables; two cards are required for 17–32 cables, etc.

B7. Next come two (or possibly three) cards of geometrical and physical data for each SC coaxial cable in the system. E.g., for three SC coaxial cables, a maximum of nine cards would be required.

B8. Next comes one card which gives the horizontal and vertical location of the center of the pipe.

B9. Next comes a frequency card, which specifies a new earth resistivity and frequency (or range of frequencies) for which cable constants are to be calculated.

B10. Only if the stratified earth modeling is being used for an overhead cable system, two additional cards are required, to give all parameters of this more complex earth model. If the earth is instead modeled as homogeneous, no such cards exist.

B11. Repeat the data of Point B9 and Point B10 , for as many different discrete frequencies or frequency ranges as may be desired. Signal the end of such data by means of a blank card.

B12. Repeat the data of Points B3 - B11 as often as may be desired. Each such grouping is a separate, distinct, independent data case within the "CABLE CONSTANTS" routine. Signal the end of such data by means of a blank card, which serves to transfer control back to the regular EMTP solution mode, ready to read a new EMTP data case.

B13. If the user wants to shut off the EMTP at this point (rather than solve a following EMTP data case), he should simply add a "BEGIN NEW DATA CASE" card at this point, followed by a blank card. This is as per Section 1.0b .

Class C Data Structure

Consider the case of a system of conventional overhead conductors, as is usually solved using the "LINE CONSTANTS" routine of Section 7.4 . An EMTP data case which uses "CABLE CONSTANTS" for this class of problem will then have input data cards ordered as follows:

C1. First comes a "BEGIN NEW DATA CASE" card (actually optional, as per Section 1.0a) .

C2. Next comes a "CABLE CONSTANTS" card, which serves to transfer control to the overlay in question (UTPF overlay number 47).

C3. Next comes a miscellaneous data card.

C4. Next come three cards for each circuit which belongs to the overhead conductor system. Parameters specified include the number of phases, the number of ground wires, the number of conductors in a bundle, geometrical data, conductor resistivity, etc. E.g., considering a system which consists of a single-circuit 500-kV transmission line and a double-circuit 230-kV transmission line all on the same right of way, nine data cards would be involved.

C5. Next comes one (or possibly more) data card which gives the height, sag, and horizontal location for the center of each bundle of each circuit of the system. One card will suffice for 1 or 2 bundles, two cards are required for 3 or 4 bundles, etc. E.g., two coupled single circuits, each of which is supported by its own towers and has a single ground wire, would require four cards (because there are eight bundles total —— four for each circuit)

C6. Next comes a frequency card, which specifies a new earth resistivity and frequency (or range of frequencies) for which line constants are to be calculated.

C7. Only if the 3-layer Nakagawa stratified earth model is being used, two additional cards are required, to complete the parameters of this more complex model of the earth. If the earth should instead be modeled as homogeneous, no such cards exi

C8. Repeat the data of Point C6 and Point C7 for as many different discrete frequencies or frequency ranges as may be desired. Signal the end of such data by means of a blank card.

C9. Repeat the data of Points C3 - C8 as often as may be desired. Each such grouping is a separate, distinct, independent data case within the "CABLE CONSTANTS" routine. Signal the end of such data by means of a blank card, which serves to transfer control back to the regular EMTP solution mode, ready to read a new EMTP data case.

C10. If the user wants to shut off the EMTP at this point (rather than execute a following EMTP data case), he should simply add a "BEGIN NEW DATA CASE" card at this point, followed by a blank card. This is as per Section 1.0b .

7.7.3 Specific Format for "CABLE CONSTANTS" Data Cards

The preceding section outlined the structure of a "CABLE CONSTANTS" data case in general terms, for each of the three different general classes of geometry which are permitted. The format and meaning of the associated data cards shall now be described in detail. Unscaled MKS units are consistently used throughout, it may be noted (e.g., distance in meters, voltage in volts, capacitance in farads, etc.).

Format for "A3" , "B3" , and "C3" data

The miscellaneous data card of Points A3 , B3 , and C3 is to be punched according to the following format:

ITYPEC	ISYST	NPC	IEARTH	KMODE	IZFLAG	IYFLAG	NPP	NGRND
I5	I5	I5	I5	I5	I5	I5	I5	I5

ITYPEC (1-5) ——— Flag which indicates the class of data case which is presently being inputted:

Class A : Punch a "2" , which implies a system of SC coaxial cables without any surrounding pipe.

Class B : Punch a "3" , which implies a system of SC coaxial cables which are enclosed within a conducting pipe.

Class C : Punch a "1" , which implies a system of conventional overhead conductors.

ISYST (6-10) —— For Class A and Class B cases, "ISYST" indicates whether the cable system is underground or in the air:

-1 ⟹ Underground (buried) cable system;

0 ⟹ Cable system is in the air, but is touching the earth's surface. See further comment elsewhere.

+1 ⟹ Cable system is in the air, above the surface of the earth.

For Class C cases, "ISYST" indicates possible transposition:

0 ⟹ Untransposed overhead line;

2 ⟹ Continuously-transposed overhead line.

NPC (11-15) —— Class A, Class B — Number of SC coaxial cables which make up the system of interest.

Class C —— The number of transmission circuits which make up the overhead system of interest. E.g., the most common case will have just NPC = 1 circuit, which will consist of three phase-conductor bundles (for a 3-phase line) and possibly one or more ground-wire bundles.

IEARTH (16-20) —— Flag indicating which model for the earth is to be used:

0 — for homogeneous (Carson) earth model;

99 — for 3-layer stratified (Nakagawa) earth model. This is allowed only for overhead systems (miscellaneous data parameter "ISYST" equal to 0 or 1).

KMODE (21-25) —— Flag used to request the calculation and output of various modal quantities of interest, as further described in Section

0 ⟹ No modal calculation or output;

1 ⟹ Modal quantities will be calculated and printed.

IZFLAG (26-30) —— Flag which indicates the format of series-impedance output (inductance, or reactance, or both) in the phase domain:

0 ⟹ Print matrices [R] and [L] ;

1 ⟹ print matrices [R] and ω[L] ;

The diagonal elements are self-impedances of the conductors and the off-diagnoal elements are the mutual impedances. For overhead lines, the order of the printout is the same as that of the phase conductors are inputted. For SC coaxial cables, the printout starts from the inner-most conductor of each cable in the order of input, then continues to the next outer layer of the conductor of each cable, etc.. For a pipe-type cable system, the last series-impedance in the printout is for the pipe.

IYFLAG (31-35) ------ Flag which indicates the format of shunt-admittance output (capacitance, or susceptance, or both) in the phase domain:

- 0 ⟹ Print matrices [G] and [C] ;
- 1 ⟹ Print matrices [G] and ω[C] ;
- 2 ⟹ print both of the above.

The order of this printout is same as that for the series-impedance.

NPP (36-40) ------ Class A, Class C ~ Unused (leave blank).

Class B ~

- 1 ⟹ pipe of finite thickness
- 0 ⟹ pipe of infinite thickness. Miscellaneous data parameter "ISYST" must also be zero, in this case.

NGRND (41-45) ------ Class A

- 0 ~ None of the outside conductors is grounded.
- 1 ~ The outside conductor of a cable is grounded.

Class B

- 0 ~ Pipe is not grounded.
- 1 ~ Pipe is grounded.

Class C ~ Unused (leave blank).

Format for "A4" and "B6" data

For cabl systems (either Class A or Class B), the number of conductors which make up each SC coaxial cable of the system must be indicated; the following format is used:

$NCPP_1$	$NCPP_2$	$NCPP_3$	$NCPP_4$	• • • • Etc.	One entry for each of NPC SC coaxial cables in System.
15	15	15	15		

$NCPP_k$ ------- The k-th SC coaxial cable of the system has this many conductors in it:

- 3 ~ for the SC coaxial cable which has all three conductors: core, sheath and armor;
- 2 ~ for the SC coaxial cable which has only two conductors: core and sheath;
- 1 ~ for the situation of a core only.

For purposes of this input, it may be noted that the SC coaxial cables have been numbered between "1" and "NPC". Such numbering is arbitrary, except that the string of $NCPP_k$ must be non-increasing (that is, all 3-conductor SC coaxial cables must precede any 2-conductor cables and all 2-conductor cables must precede any core only cables). this ordering, once established, is assured to apply throughout the rest of the data case.

Format for "B4" data

Point B4 data consists of a single card, upon which the user is to punch various parameters of the pipe. The following format applies:

RP_1	RP_2	RP_3	ρ	μ_r	ϵ_1	ϵ_2
E10.1	E10.1	E10.1	E10.1	E10.1	E10.1	E10.1

RP_1 —— Inner radius of the pipe, in units of meters.

RP_2 —— Outer radius of the pipe, in units of meters.

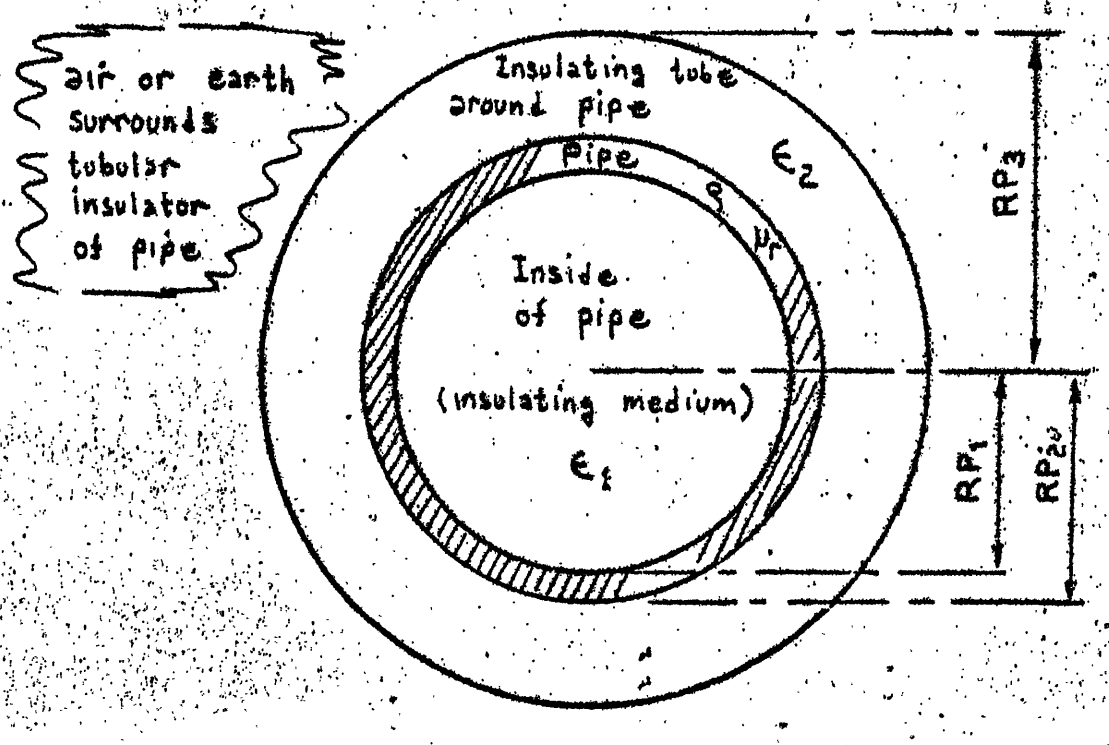
RP_3 —— Outer radius of the tubular insulator which surrounds the pipe, in units of meters.

ρ —— Resistivity of the pipe, in units of ohm-meters.

μ_r —— Relative permeability of the pipe. This is a dimensionless number, the ratio of the permeability of the pipe to the permeability of free space.

ϵ_1 —— Relative permittivity of the insulating medium which is inside the pipe (between the pipe and the SC coaxial cables which are contained). This is a dimensionless quantity, the ratio of the permittivity of the inner insulating medium to the permittivity of free space.

ϵ_2 —— Relative permittivity of the insulating tube which surrounds the pipe. This is a dimensionless quantity.



Format for "C4" data

For each circuit of the system of conventional overhead conductors which is being studied, three data cards of the following format are to be punched.

NP	NG	KBP	KBG
I5	I5	I5	I5

$ROUT_P$	RIN_P	$ROUT_G$	RIN_G	SEP_P	SEP_G
E10.1	E10.1	E10.1	E10.1	E10.1	E10.1

ρ_P	μ_P	ρ_G	μ_G
E10.1	E10.1	E10.1	E10.1

NP ——— The number of phase-wire bundles which belong to the circuit in question. E.g., for a 3-phase circuit, "NP" will equal three.

NG ——— The number of ground-wire bundles which belong to the circuit in question.

KBP ——— The number of individual physical conductors which compose each phase-wire bundle of the circuit in question. If there is no bundling of phase wires, "KBP" will equal unity.

KBG ——— The number of individual physical conductors which compose each ground-wire bundle of the circuit in question. If there is no bundling of ground wires, "KBG" will equal unity.

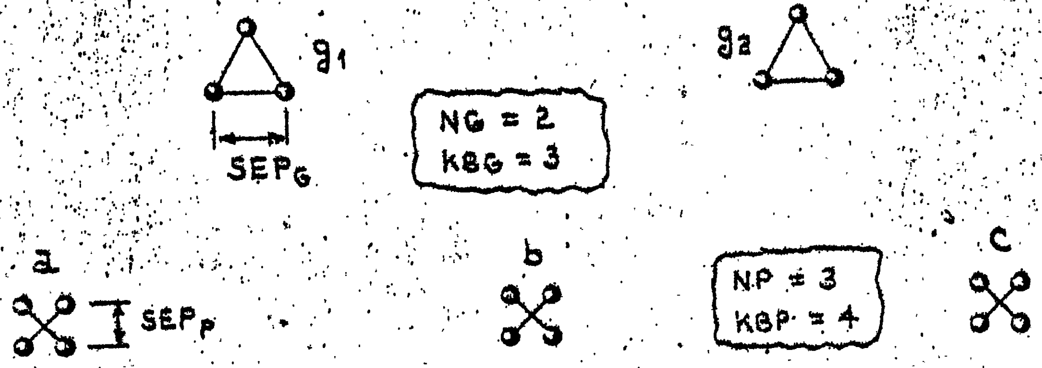
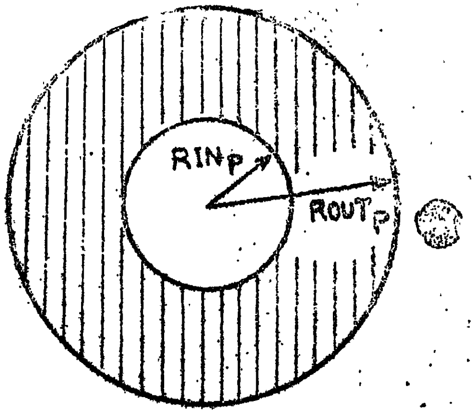


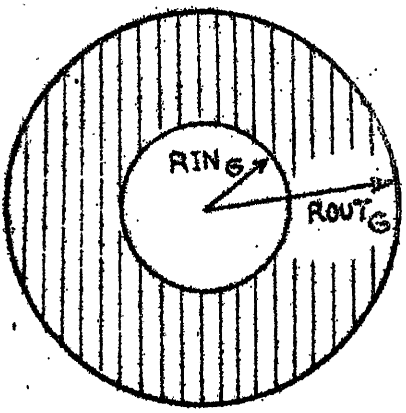
Fig. 5. Illustrative single-circuit 3-phase overhead transmission line (as seen in cross-section). The three phase-wire bundles are of four conductors each; there are two ground-wire bundles, of three conductors each.

$ROUT_P$ ——— Outer radius of the tubular conductors which are used for each phase-wire bundle of the circuit in question. Units are meters .



RIN_P ——— Inner radius of the tubular conductors which are used for each phase-wire bundle of the circuit in question. Units are meters .

$ROUT_G$ ——— Outer radius of the tubular conductors which are used for each ground-wire bundle of the circuit in question. Units are meters .



RIN_G ——— Inner radius of the tubular conductors which are used for each ground-wire bundle of the circuit in question. Units are meters .

SEP_P ——— Separation between centers of two adjacent conductors of any one of the phase-wire bundles. Units are meters . The "KBP" conductors of the bundle are assumed to be uniformly spaced around the circumference of a circle.

SEP_G ——— Separation between centers of two adjacent conductors of any one of the ground-wire bundles. Units are meters . The "KBG" conductors of the bundle are assumed to be uniformly spaced around the circumference of a circle.

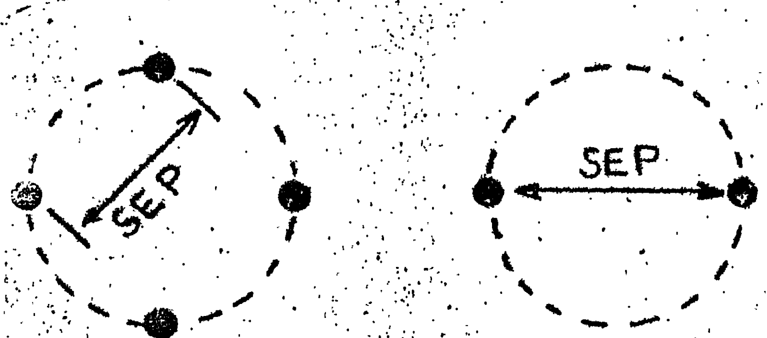


Fig. 8. Illustration of two different bundles; that on the left has four conductors, while the bundle on the right has only two. Note the uniform spacing.

ρ_P ——— Resistivity of the material used in each tubular conductor of each phase-wire bundle of the circuit under consideration. Units are ohm-meters .

μ_P ——— Relative permeability of the material used in each tubular conductor of each phase-wire bundle of the circuit under consideration. This is a dimensionless quantity.

671

ρ_G ——— Resistivity of the material which is used in each tubular conductor of each ground-wire bundle of the circuit under consideration. Units are ohm-meters.

μ_G ——— Relative permeability of the material which is used in each tubular conductor of each ground-wire bundle of the circuit under consideration. This is a dimensionless quantity.

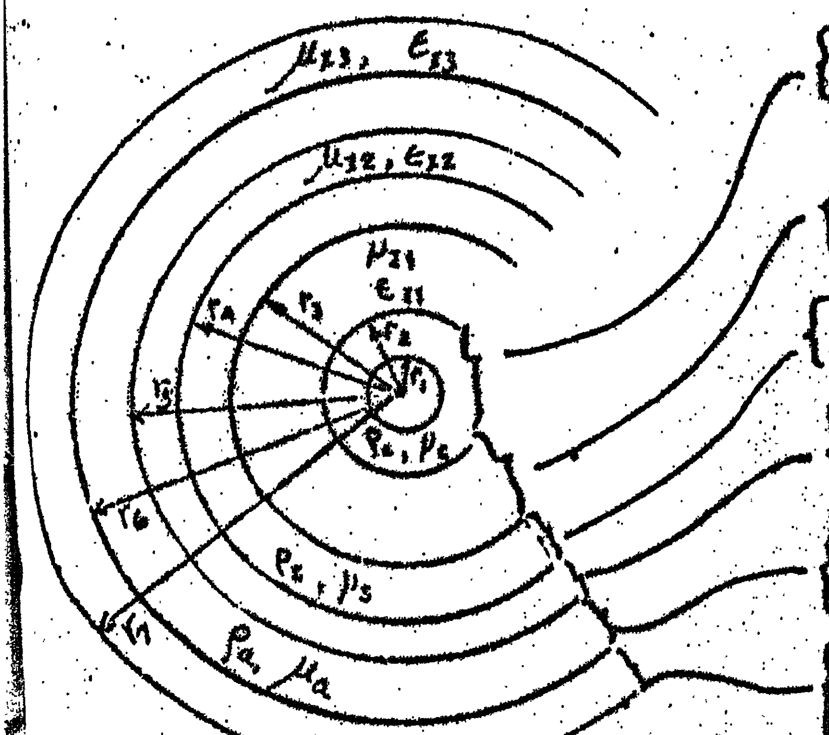
Format for "A5" and "B7" data

For each SC coaxial cable of the system, a maximum of three data cards are to be punched according to the following format. Such cards are to be stacked in the circuit order which was defined for Point "A4" data.

r_1	r_2	r_3	r_4	r_5	r_6	r_7
E10.1	E10.1	E10.1	E10.1	E10.1	E10.1	E10.1

ρ_c	μ_c	μ_{I1}	ϵ_{I1}	ρ_s	μ_s	μ_{I2}	ϵ_{I2}
E10.1	E10.1	E10.1	E10.1	E10.1	E10.1	E10.1	E10.1

ρ_a	μ_a	μ_{I3}	ϵ_{I3}
E10.1	E10.1	E10.1	E10.1



{ Tubular core (subscript "c") of the SC coaxial cable.

{ 1st insulation layer (subscript "I1"), which lies between the core and the sheath.

{ Tubular sheath (subscript "s") of the SC coaxial cable.

{ 2nd insulation layer (subscript "I2"), which surrounds the sheath.

{ Tubular armor (subscript "a") of the SC coaxial cable.

{ 3rd insulation layer (subscript "I3"), which surrounds the armor.

r_1 —— Inner radius of the tubular core, for the SC coaxial cable under consideration. Units are meters .

r_2 —— Outer radius of the tubular core (equal to the inner radius of the first insulating layer), for th SC coaxial cable under consideration. Units are meters .

r_3 —— Inner radius of the sheath (equal to the outer radius of the first insulating layer), for the SC coaxial cable under consideration. Units are meters .

r_4 —— Outer radius of the sheath (equal to the inner radius of the second insulating layer), for the SC coaxial cable under consideration. Units are meters .

r_5 —— Inner radius of the armor (equal to the outer radius of the second insulating layer), for the SC coaxial cable under consideration. Units are meters .

r_6 —— Outer radius of the armor (equal to the inner radius of the third insulating layer), for the SC coaxial cable under consideration. Units are meters .

r_7 —— Outer radius of the third (outer-most) layer of insulation, for the SC coaxial cable under consideration. Units are meters .

ρ_c —— Resistivity of the tubular core, for the SC coaxial cable under consideration. Units are ohm-meters .

μ_c —— Relative permeability of the tubular core, for the SC coaxial cable under consideration. This is a dimensionless quantity.

μ_{I1} —— Relative permeability of the 1st insulating layer. This is a dimensionless quantity.

ϵ_{I1} —— Relative permittivity of the 1st insulating layer. This is a dimensionless quantity.

ρ_s —— Resistivity of the tubular sheath, for the SC coaxial cable under consideration. Units are ohm-meters .

μ_s —— Relative permeability of the tubular sheath. This is a dimensionless quantity.

μ_{I2} —— Relative permeability of the 2nd insulating layer. This is a dimensionless quantity.

ϵ_{I2} —— Relative permittivity of the 2nd insulating layer. This is a dimensionless quantity.

673

ρ_a ——— Resistivity of the tubular armor, for the SC coaxial cable under consideration. Units are ohm-meters .

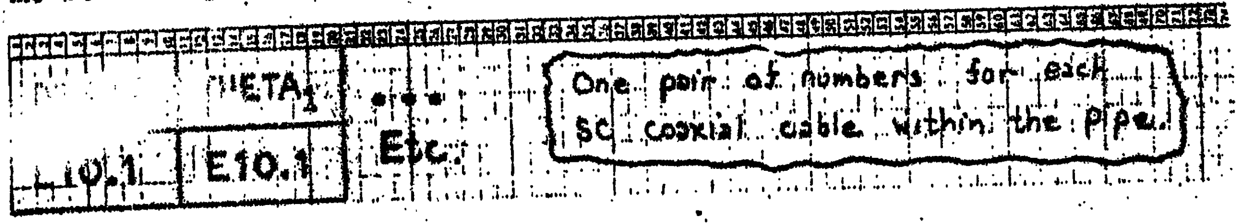
μ_a ——— Relative permeability of the tubular armor. This is a dimensionless quantity.

μ_{I3} ——— Relative permeability of the 3rd insulating layer. This is a dimensionless quantity.

ϵ_{I3} ——— Relative permittivity of the 3rd insulating layer. This is a dimensionless quantity.

Format for "B5" data

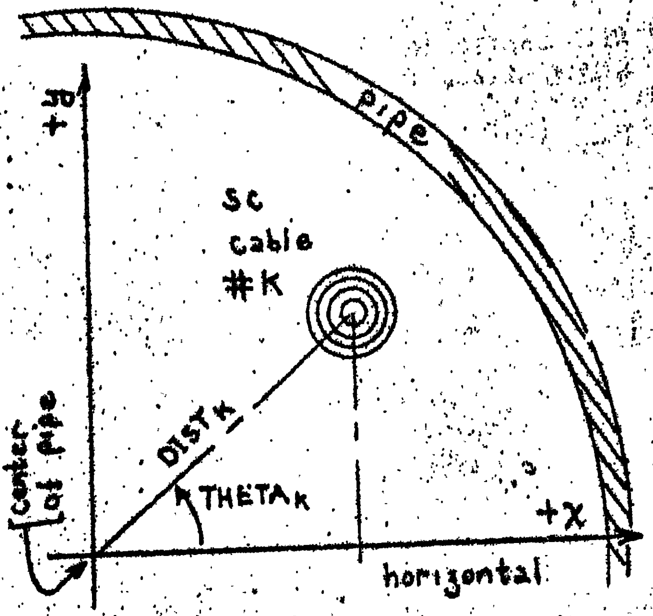
The location of each of the "NPC" SC coaxial cables within the surrounding conducting pipe is specified by one (or possibly more) card of the following format:


THETA1
10.1
E10.1
• • •
Etc.
One pair of numbers for each SC coaxial cable within the pipe.

DIST$_k$ ——— Distance between the center of the pipe and the center of the k-th SC coaxial cable, in units of meters .

THETA$_k$ ——— Angular position of the k-th SC coaxial cable, in units of degrees.

Here the pair (DIST$_k$, THETA$_k$) is simply the conventional polar coordinate location of the k-th SC coaxial cable. The origin is taken to be the center of the pipe (see sketch), with the positive x-axis directed horizontally to the right.



Format for "C5" data

For each bundle of the overhead conductor system, a triplet of numbers giving the horizontal and vertical location is to be supplied, according to the following format:

$VTOWER_1$	$VMID_1$	$HORIZ_1$
E10.1	E10.1	E10.1

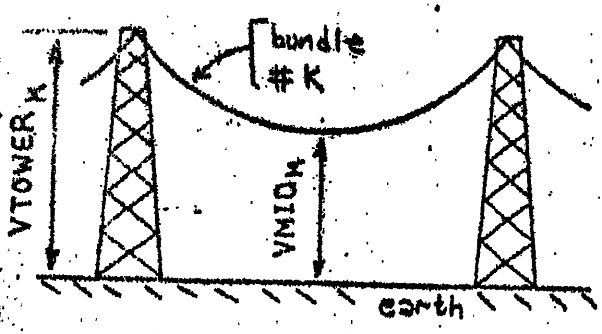
• • • Etc.

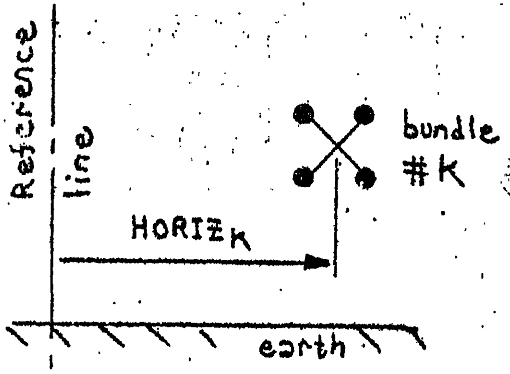
One triplet of numbers for each bundle of the system

$VTOWER_k$ ——— Height above the earth's surface of the center of the k-th bundle; this is height in meters, at the tower (the maximum height).

$VMID_k$ ——— Height above the earth's surface of the center of the k-th bundle; this is height in meters, at mid-span (the minimum height).

$HORIZ_k$ ——— The center of the k-th bundle is this far to the right of an arbitrarily chosen reference line.





With regard to the ordering of the bundles which belong to the system under study (i.e., index "k"), two rules must be observed:

Rule 1 : First come all phase-wire bundles of the system, in order of the circuit number to which they belong (as established by Point C4 data). I.e., start with all phase-wire bundles of circuit number one; then consider all of the phase-wire bundles of circuit number two, etc.

Rule 2 : Then come all (if there are any) ground-wire bundles of the system, in order of the circuit number to which they belong (as established by Point C4 data). I.e., start with all ground-wire bundles of circuit number one, if any; then consider all of the ground-wire bundles of circuit number two, etc.

Within any one circuit, ordering of the phase-wire bundles and the ground-wire bundles is arbitrary. Rows of the resulting line constants matrices [R], [L], and [C] will be based on this ordering, however, it might be noted. See the example of Section

Format for "A6" data

For each of the "NPC" SC coaxial cables of the system, horizontal and vertical coordinates which locate the center must be specified, as follows:

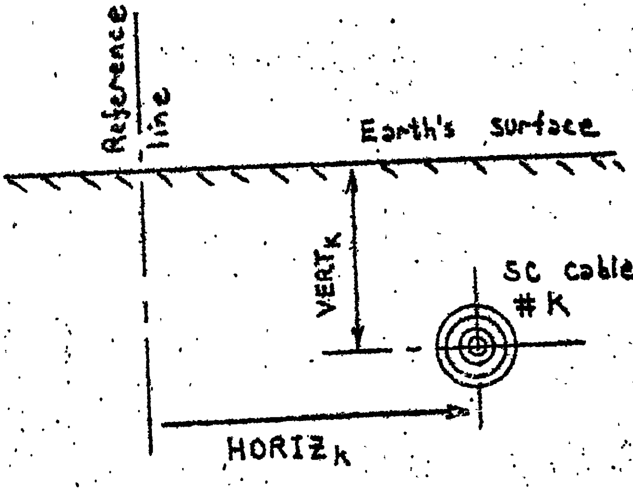
SC Cable #1		SC Cable #2		. . .
ERT$_1$	HORIZ$_1$	VERT$_2$	HORIZ$_2$	Etc.
	E10.1	E10.1	E10.1	

One entry for each of NPC SC coaxial cables in the system.

VERT$_k$ ——— Vertical separation between the center of the k-th SC coaxial cable and the surface of the earth, in units of meters . This is always a positive number, whether the system of SC coaxial cables is below the ground or not.

HORIZ$_k$ ——— The center of the k-th SC coaxial cable is this far (in meters) to the right of an arbitrary reference line.

Here the ordering of the SC coaxial cables (i.e., index "k") is as was established in Point A4 data.



Format for "C6" , "A7" , and "B9" data

The "frequency card" of all three classes of data cases has the same format:

O	FREQ	IDEC	IPNT	DIST	IPUN
E15 6	E15.6	I5	I5	F8.3	I10

RHO (1-15) ——— Resistivity of the top (i.e., surface) layer of the earth, in units of ohm-meters .

If the earth is assumed to be homogeneous (parameter "IEARTH" equal to zero; see Point A3, B3, or C3 data), "RHO" is the resistivity of the entire uniform earth.

FREQ (16-30) ——— Frequency in Hertz at which cable constants (for "A7" or "B9" data) or line constants (for "C6" data) ar to be calculated, should only one frequency be desired.

A blank or zero field will be defaulted to the synchronous power system frequency (generally 50 Hz or 60 Hz), as defined by variable "STATFR" of installation-dependent module..."SYSDEP" of UTPF overlay number 1 .

If the automatic looping over logarithmically-spaced frequencies has been requested by the user (parameter "IDEC" of columns 31-35 greater than zero), then "FREQ" is the beginning (i.e., the lowest) frequency of the scan.

IDEC (31-35) ------ Leave blank for the normal single-frequency calculation. But if the user wants automatic looping over logarithmically-spaced frequencies, then "IDEC" is the number of decades of frequency space which are to be spanned.

IPNT (36-40) ------ Leave blank for the normal single-frequency calculation. But if the user wants automatic looping over logarithmically-spaced frequencies, then "IPNT" is the number of points per decade of frequency space at which [R], [L], and [C] are to be calculated.

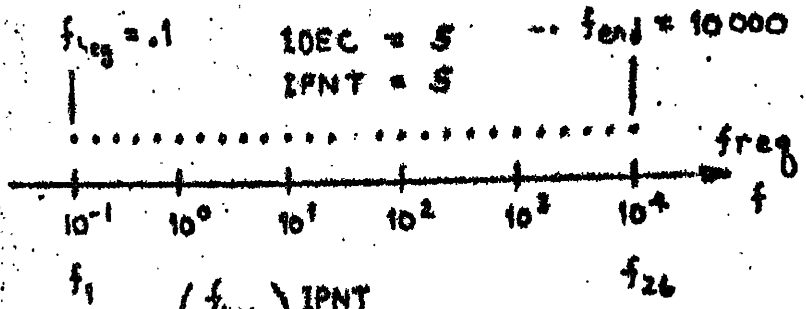
DIST (41-48) ------ Length of the transmission circuit under consideration, in units of meters . This field can usually be left blank. It need be punched only for the following situations:

1) For use with "SEMLYEN SETUP" ; see Section 7.5 .
2) For use with "AMETANI SETUP" ; see Section 7.6 .

IPUN (49-58) ------ Normally this field is left blank. It is used to request non-printed output of modal quantities, for the case where there is automatic internal looping over logarithmically-spaced frequencies. Punch :

"88" ------ For the connection of zero-sequence (ground mode) impedances with "WEIGHTING" . This has meaning only when a "CABLE CONSTANTS" data case is imbedded in a "WEIGHTING" data case.

"89" ------ As just described for "88" , only for the Karrenbauer line mode (rather than for the ground mod).



$$\left(\frac{f_{k+1}}{f_k}\right)^{IPNT} = 10$$

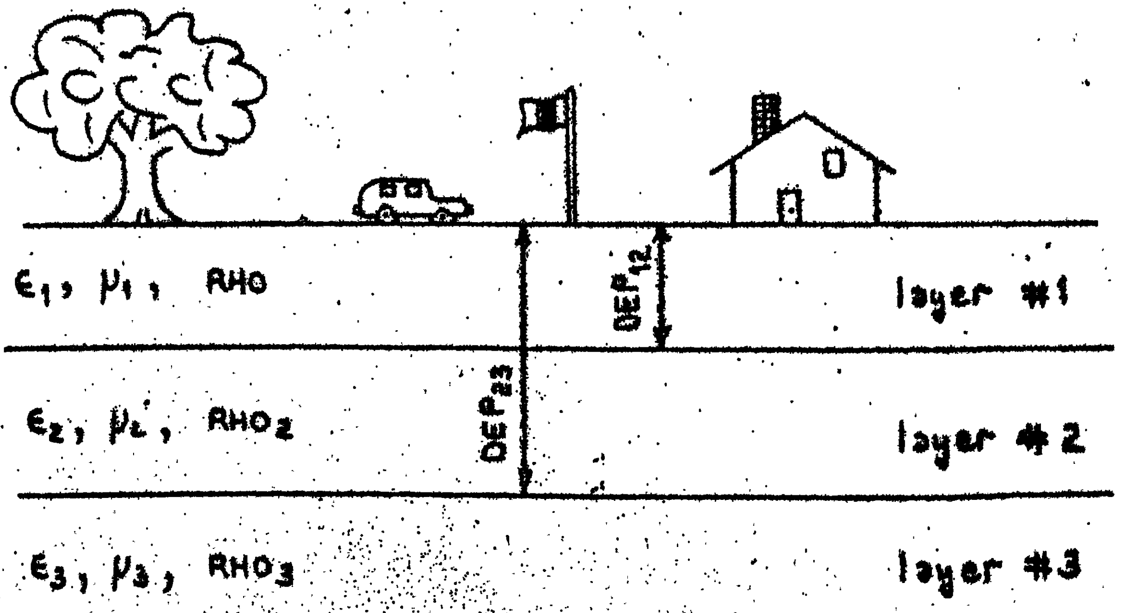
Format for "C7" , "A8" , and "B10" data

If the 3-layer stratified (Nakagawa) earth modeling is being used, then the just-described "frequency card" is to immediately be followed by two cards of the following format:

DEP_{12}	DEP_{23}	RHO_2	RHO_3
E10.1	E10.1	E10.1	E10.1

	μ_2	μ_3	ϵ_1	ϵ_2	ϵ_3
E10.1	E10.1	E10.1	E10.1	E10.1	E10.1

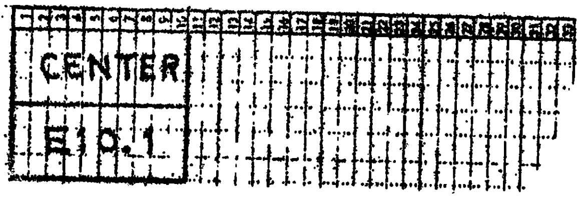
DEP_{12} (1–10) ——— Distance below the surface of the earth at which layer number 1 ends and layer number 2 begins. Units are meters . See sketch below.


DEP_{12}
DEP_{23}
ϵ_1, μ_1, RHO
layer #1
ϵ_2, μ_2, RHO_2
layer #2
ϵ_3, μ_3, RHO_3
layer #3

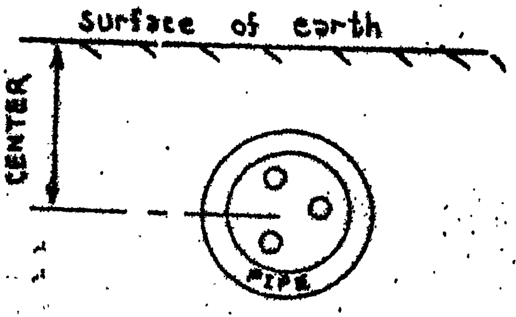
DEP$_{23}$ (11-20)	Distance below the surface of the earth at which layer number 2 ends and layer number 3 begins. Units are meters . Recall that layer number 3 is infinitely deep.
RHO$_2$ (21-30) RHO$_3$ (31-40)	Resistivities of layers number 2 and 3 of the earth, respectively. Units are ohm-meters . Recall that "RHO" of the frequency card is used to specify the resistivity of layer number 1 .
μ_1 μ_2 μ_3	Relative permeabilities of layers number 1 , 2 , and 3 of the earth, respectively. These are dimensionless quantities.
ϵ_1 ϵ_2 ϵ_3	Relative permittivities of layers number 1 , 2 , and 3 of the earth, respectively. These are dimensionless quantities.

Format for "B8" data

The vertical distance between the center of the pipe (which encloses the SC coaxial cables) is to be punched according to the following format:



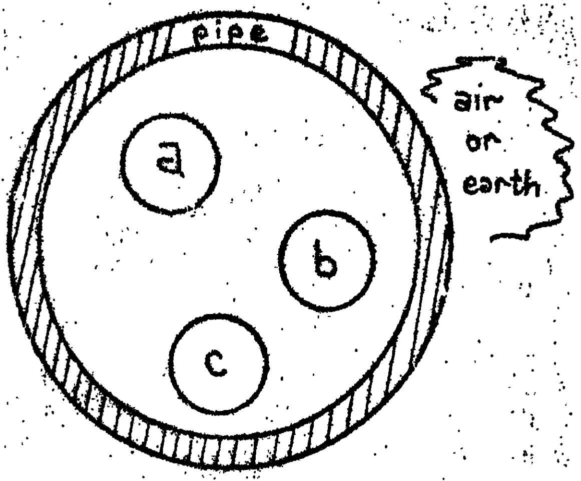
This figure is always positive, whether the pipe is below the ground or not. Units used are meters .



7.7.4 Degenerate Configurations and Special Cases

It is the purpose of the present section to describe how the user of "CABLE CONSTANTS" can handle special configurations which are less general than those described in Section 7.7.3 .

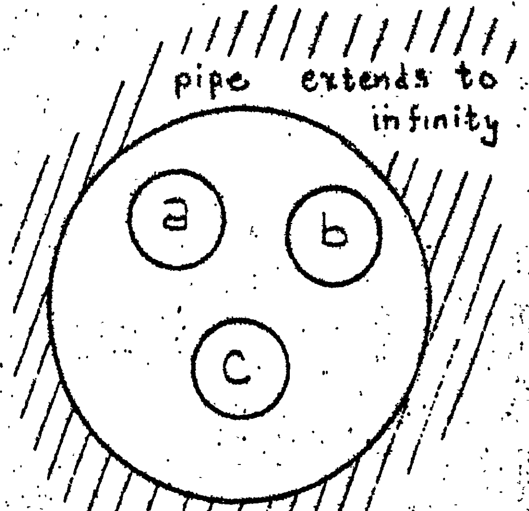
A) Pipe without tubular insulator around it



Suppose that a pipe-type (Class B) configuration is involved, but without any insulating tube around the outside of the conducting pipe. Then Point B4 data is to be treated as follows:

1. Leave RP_3 (columns 21-30) blank.
2. Leave the data field for ϵ_2 (columns 61-70) blank.

B) Infinitely-thick pipe



While physically unrealizable, a pipe of infinite thickness is nonetheless useful in certain situations as a modeling proximation. This is a special case of the Class B situation. By definition, there is no earth for this case, and all zero-sequence current of the enclosed SC coaxial cables must return through the pipe Data requirements for this special case are as follows:

1. On the Point B3 miscellaneous data card, two parameters are to be punched unusually:

   "ISYST" of columns 6-10 is to be punched zero;

   "NPP" of columns 36-40 is to be punched zero (rather than the usual value of unity).

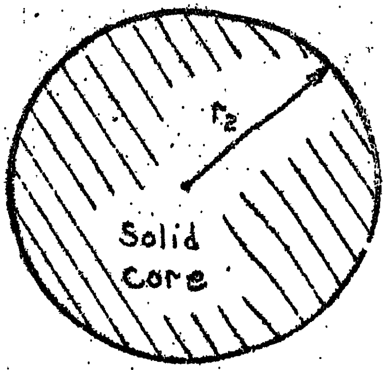
2. On the Point B4 data card, three data fields can be left blank:

   "RP_2" of columns 11-20 —— since the outer radii of the pipe and the surrounding insulator are not even finite.
   "RP_3" of columns 21-30

   "ϵ_2" of columns 61-70 —— since the surrounding insulator does not even exist (or if it does, it is infinitely far away!).

3. On the "frequency card" of Point B9 data, field RHO" of columns 16-30 can be left blank —— since the earth no longer exists.

C) Solid core for SC coaxial cable

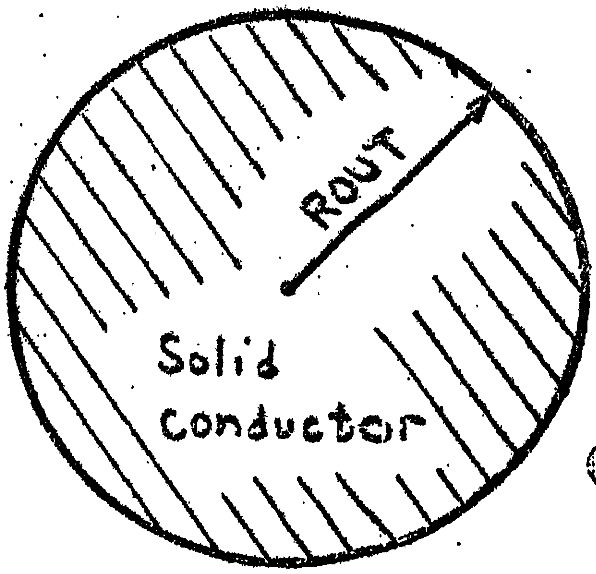


For either Class A or Class B cable systems, the core of any SC coaxial cable can be made solid rather than tubular, if so desired. The first of two Point A5 or Point B7 data cards has columns 1-10 used for punching the inner radius r_1 of the tubular core. Simply set this parameter to zero, to produce a solid core.

D) Solid overhead-line conductors

For a conventional overhead transmission line of Class C, the conductors of either the phase-wire bundles or the ground-wire bundles can be made solid, rather than tubular, if so desired. Recall that the second of three Point C4 data cards is punched with an inner radius RIN_P for phase-wire conductors, and RIN_G for ground-wire conductors.

1. Set RIN_P of columns 11-20 equal to zero, in order to obtain solid conductors for the phase wires.
2. Set RIN_G of columns 31-40 equal to zero, in order to obtain solid conductors for the ground wires.



E) No bundling of conductors

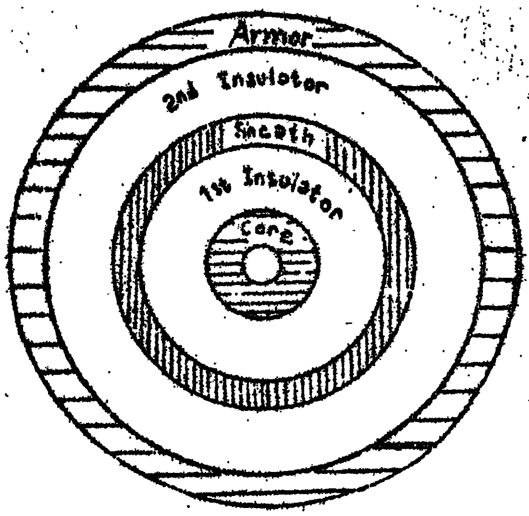
For a conventional overhead transmission line of Class C, it is Point C4 data which specifies whether phase-wire or ground-wire conductors are to be bundled.

1. If a phase-wire bundle only consists of a single tubular conductor (i.e., if there is no bundling of phase conductors), then "KBP" of columns 11-15 of the first Point C4 data card will be punched equal to unity, by definition. Field SEP_P of columns 41-50 of the second Point C4 data card can then be left blank ------ since interconductor separation within a phase-wire bundle does not exist.
2. If a ground-wire bundle only consists of a single tubular conductor (i.e., if there is no bundling of ground conductors), then "KBG" of columns 16-20 of the first Point C4 data card will be punched equal to unity, by definition. Field SEP_G of columns 51-60 of the second Point C4 data card can then be left blank ------ since interconductor separation within a ground-wire bundle does not exist.

F) SC coaxial cable without outer insulator

For a Class A or Class B data case, the outer (or 3rd) layer of insulation of any SC coaxial cable can be omitted. In this case, the three Point A5 or Point B7 data cards are handled as follows:

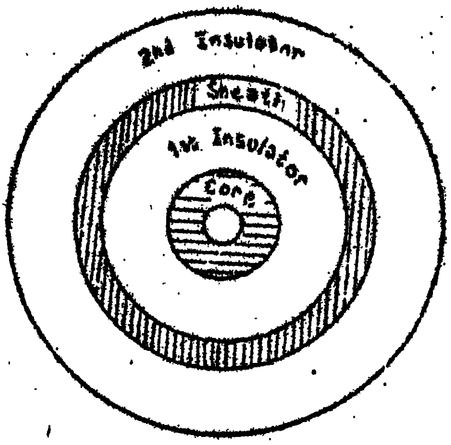
1. Leave r_7 (columns 61-70) of the first card) blank.
2. Leave data fields μ_{I3} and ϵ_{I3} (columns 31-40 of the third card) blank ---- since such parameters do not exist.



G) SC coaxial cable with no armor and no outer insulator

For a Class A or Class B data case, both the armor and the outer (or 3rd) layer of insulation of any SC coaxial cable can be omitted. In this case, the three Point A5 or Point B7 data cards are handled as follows:

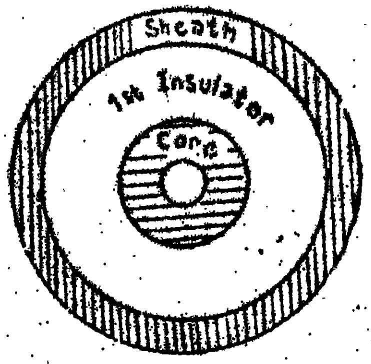
1. Leave r_7 and r_6 (columns 51-70 of the first card) blank.
2. Omit the 3rd data card because of the nonexistence of ρ_a, μ_a, μ_{I3} and ϵ_{I3}.



H) SC coaxial cable with no armor and no outer insulators

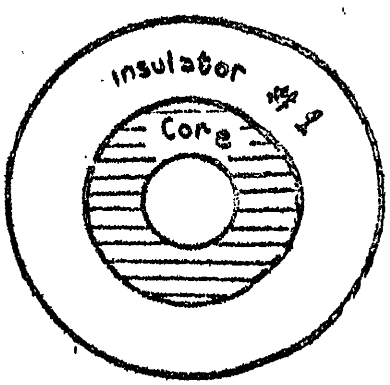
For a Class A or Class B data case, the outer (2nd and 3rd) layers of insulation and armor of any SC coaxial cable can be omitted. In this case, the three Point A5 or Point B7 data cards are handled as follow :

1. Leave r_7, r_6 and r_5 (columns 41-70 of the first card) blank.
2. Leave data fields μ_{I2} and ϵ_{I2} (columns 61-80 of the second card) blank and omit the third card ---since such parameters do not exist.



2) SC coaxial cable with not sheath and no outer insulators

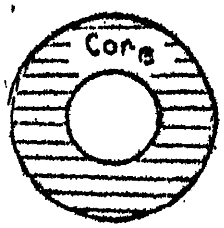
For a Class A or Class B data case, both the sheath, armor and the outer (2nd and 3rd) layers of insulation of any SC coaxial cable can be omitted. In this case, the three Point A5 or Point B7 data cards are handled as follows:



1. Leave r_7, r_6, r_5 and r_4 (columns 31-70 of the first card) blank.
2. Leave blank all other data fields which are used for parameters of the nonexistent sheath and outer insulator. In particular, there are four: ρ_s, μ_s, μ_{I2} and ϵ_{I2} (columns 41-80 of the 2nd card).
3. Omit the third card --- since parameters for armor and its outer insulator do not exist.

3) SC coaxial cable having core only (all three insulators, armor and sheath missing)

For a Class A or Class B data case, the armor, sheath and all three layers of insulation of any SC coaxial cable can be omitted, leaving just the tubular conductor core. In this case, the three Point A5 or Point B7 data cards are handled as follows:

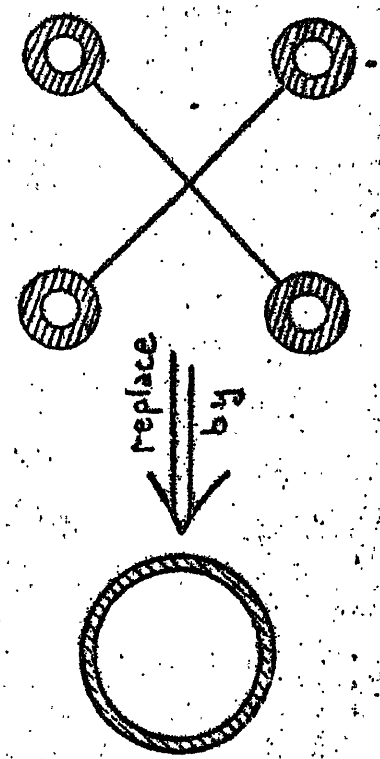


1. Leave r_7, r_6, r_5, r_4 and r_3 (columns 21-70 of the first card) blank.
2. Leave blank all other data fields which are used for parameters of the nonexistent sheath and layers of insulation. In particular, there are six: μ_{I1}, ϵ_{I1}, ρ_s, μ_s, μ_{I2} and ϵ_{I2} (columns 21-80 of the 2nd card).
3. Omit the third card ---since the parameters for armor and its outer insulator do not exist.

269 d

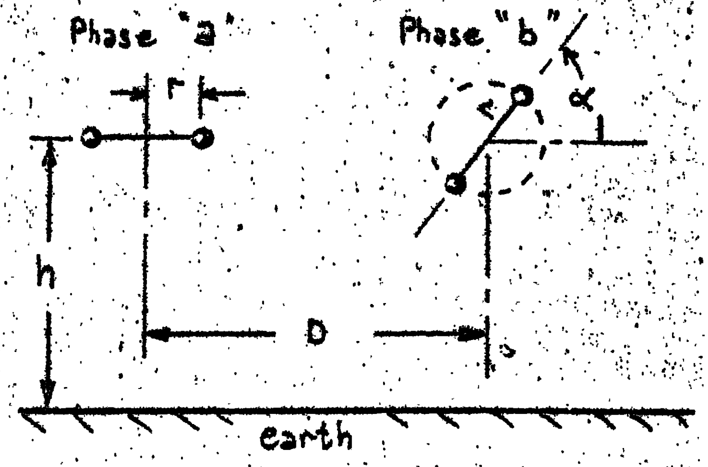
7.7.5 Approximation Used for the Bundling of Overhead Conductors

It is important for the user to be aware that "CABLE CONSTANTS" treats bundled conductors of conventional overhead transmission lines quite differently than does "LINE CONSTANTS" of Section 7.4 . The reader may already have realized this, since the Point 04 data is not sufficient to uniquely specify the geometry of a bundle. No angular po ition of any one conductor of the undle is specified, it will be noted.



The "LINE CONSTANTS" code of ection 7.5 calculates line constants or the system of physical conductors first. his is then reduced, as conductors are arallelod (the bundling operation). On he other hand, "CABLE CONSTANTS" does he bundling at data-input time. The eometric mean radius of the bundle is mmediately calculated, and then a single pproximately equivalent conductor is represent each bundle for the ion of line constants. There is any set of line constants for e system of physical conductors, then, en using "CABLE CONSTANTS" .

Needless to say, this bundling of nductors at data-input time simplifies e calculation considerably, and speeds up. But an approximation is involved. order to estimate the error, line nstants have been calculated for the phase geometry shown at the right. e "LINE CONSTANTS" code was ed, for two different values of the le α : zero degrees and 90 The radius of the bundles , the average height "h" , the paration "D" , and the frequency "f" re also varied. In all cases, a ductor diameter of 1.093 inches was d, and ground resistivity was fixed at ohm-meters. Results are summarized h following tabulation:



Sorry! Example nev r completed; no next page.

7.8 "HAUER SETUP" Routine

By means of the special request word "HAUER SETUP", an EMTP user gains access to the supporting routine which bears this same name, as per the explanation of Section 7. . The principal function of this code is to output the branch cards which are needed for the representation of a transmission circuit using recursive convolution scheme. See Section 1.27.

As mentioned in Section 0.2, item 9, Section 7., and the last paragraph of Section 7.5, "HAUER SETUP" routine originated by Dr. John Hauer of BPA is a very sophiscated frequency-domain fitting program. Since the work started in September, 1979, two BPA internal reports, dated October 5, 1979 and April 22, 1980 have been written by Dr. Hauer to summarize the progress made on the work of "HAUER SETUP" in the EMTP. The theory behind this routine can be found in Dr. Hauer's BPA internal memo, dated May 7, 1980. A copy of this is available upon request.

Up to this date (May 23, 1980), finer tuning to the code is still being worked on by Dr. Hauer.

7.8.1 Structure of "HAUER SETUP"

"HAUER SETUP" consists of two EMTP segments, Overlays 48 and 49 Program controls and the setup data output follow the "SEMLYEN SETUP" convensions as far as possible, to facilitate prototype comparisons.

7.8.1.1 Overlay 48

This is an abridged and restructured version of Overlay 45 (SEMLYEN SETUP). Its main purpose is to generate frequency response data for wave propagation, characteristic admittance, and the transformation matrices. The wave propagation and characteristic admittance data are written on LUNIT8.

The data input for "HAUER SETUP" is quite similar to that for "SEMLYEN SETUP". See Section 7.5. An example of "HAUER SETUP" data case is shown in the following:

```
BEGIN NEW DATA CASE
HAUER SETUP
BRANCH  BEGINAENDA  BEGINBENDB  BEGINCENDC
TOLERANCES  18      40.     17   12.
                         1 0 1 0 0 1
LINE CONSTANTS                                                        60  1
  1.3636 .05215  4          1.602  -20.75   50.      50.
  1.3636 .05215  4          1.602  -19.25   50.      50.
  2.3636 .05215  4          1.602   -0.75   77.5     77.5
  2.3636 .05215  4          1.602    0.75   77.5     77.5
  3.3636 .05215  4          1.602   19.25   50.      50.
  3.3636 .05215  4          1.602   20.75   50.      50.
  0.5     2.61   4          0.386  -12.9    50.      50.
  0.5     2.61   4          0.386   12.9    98.5     98.5
BLANK CARD TERMINATING CONDUCTOR CARDS.    98.5     98.5
 27.        60.          1                     138.
 27.        6.0          1                     138.             9 21
BLANK CARD TERMINATING FREQUENCY CARDS.
BLANK CARD TERMINATING LINE CONSTANTS CASES.
$INCLUDE,SYSFITCON.DAT,2
BEGIN NEW DATA CASE
BLANK CARD TERMINATING RUN
```

Discussion on data cards of the just shown example will be given only to the two (indicated by boxes) that are different from "SEMLYEN SETUP":

1) Miscellaneous data card
The misc. data card for "HAUER SETUP" has the following format:

TEXT		NSS	MSSPI	KPS	KYC	[illegible]	[illegible]	IOTX	IOSS	IOFL		MDBBW	IPRCON	MODETX	MFRTST
A8	10X	I2	I2	I2	I2	I2	I2	I6	I6	I6	21X	I3	I3	I3	I2

Many of these variables are also used in "SEMLYEN SETUP" and have the same meaning here, except that the options for KPS = 2 and KYC = 3 are not honored in "HAUER SETUP". New variables are:

MSSPI	If ≠ 1, logic in Overlay 49 will adjust the steady-state Pi values to agree with the model response at steady-state frequency f.
MDBBW	If ≠ 1, frequency response data cutoff occurs when wave response is down by MDBBW decibels, rather than the standard 40db.
IPRCON	A printout control, for which a level between 0 and 3 is usually appropriate. Increasing values produce further diagnostic output.

MODETX and MFRTST are experimental controls that should normally be set to zero.

2) $INCLUDE, FILE, M Card
The control parameters for the fitting program "SYSFIT" are contained in a file (The details of these fitting parameters will be explained in the next section). This file is read in by using the new "$INCLUDE" feature of "CIMAGE" routine (see Section 0.5), item D5). In the example shown, the name of the file (FILE) is SYSFITCON.DAT; the scratch unit (M) that SYSFITCON.DAT will be written on is LUNIT2.

27121

7.8.1.2 Structure of SYSFIT Control Data File

SYSFIT control data is read from logical unit LU5. Prototype control data files for EMTP use are stored on the VAX computer as SYSFITCON.DAT, LINEFITC.DAT, and CABLEFITC.DAT. A standard version of LINEFITC.DAT is shown on the next page. Those controls which the user may wish to modify are indicated by a box. There are 2 of these among the search controls: the maximum number of iterations (shown as 200), and a printout suppression flag (shown as 1). Search for the optimal point will terminate in fewer than the maximum number of iterations if the gradient of the fitting-error function falls below the given tolerance value. A further printout control appears on the line following the tolerance specification. The entry 2 shown will produce a display of the model-to-data fit after optimization; a value of 3 will yield an additional display of the model fit prior to optimization. Higher values of the printout supression flag will progressively override this. The rewind flag (-7) leads to the reuse of the SYSFIT controls for the next mode. This process is terminated by an END card or an end-of-file(EOF) record on LUNIT8.

The first 5 lines of the data constitute inputs to the general optimization routines (MORPAK), whereas the lines from there through the first -10 flag are inputs unique to the system fitting problem. These are addressed separately in the following:

Search Controls

```
Tolerance  →           [1.E-4]     0. [200]   2    2    2    2    0   [1]
              [2]    0    1    1    1    0    1
              -1     1    1  211   -2    2    2    0
               0     1
            **8-BLOCK WAVE PROPAGATION MODEL (1 TIME DELAY)
               8     0
        ⎧      1     1    1    1    0    0    9    0    0
 LockX  ⎨      0    14    0    0    1    0   19    0    0    1
        ⎩      0    24    0    0    1    0   29    0    0    1
               0    34    0    0    1    0   39    0    0    1
        ⎧   0.00000000E+00 0.00000000E+00 0.00000000E+00 0.10000000E+01 0.00000000E+00=   9
        ⎪  -0.10247659E+02 0.50524911E+01-0.51150683E+01 0.50524911E+01 0.00000000E+00*   1
        ⎪  -0.18142660E+02 0.18376627E+02-0.44030099E+02 0.18376627E+02 0.00000000E+00*   1
   X    ⎨  -0.40847924E+02 0.16202238E+03-0.44195595E+02 0.16202238E+03 0.00000000E+00*   1
        ⎪  -0.22244432E+03 0.13556427E+04-0.53432068E+02 0.13556427E+04 0.00000000E+00*   1
        ⎪  -0.27573748E+03 0.17956693E+04-0.45660046E+02 0.17956693E+04 0.00000000E-00*   1
        ⎪  -0.41615307E+00 0.11511473E+02-0.34450242E+01 0.11511473E+02 0.00000000E+00*   1
        ⎩  -0.23132415E+02 0.30696716E+03-0.45923651E+02 0.30696716E+03 0.00000000E+00    1
           SCALE FRED               PASSBAND    1.0
 Termination ⎧ END
 Flags       ⎩
               -10
- - - - - - - **FIT ED CHARACTERISTIC ADMITTANCE RESPONSE
Search Controls →  0    0    0    0  [200]   2    2    2    2    0   [1]
   Tolerance    →       [1.E-6]
              [2]    0    1    1    1    0    1
              -1     1    1  211   -2    2    0    0
               0     1
            **3-BLOCK CHARACTERISTIC ADMITTANCE MODEL
               3     0
 LockX  ⎧      1     1    1    1    0    0    0    0    0    1
        ⎩      0     0    0    0    1
        ⎧   0.00000000E+00 0.00000000E+00-0.314        E+01 0.00000000E+00 1.0          E+00=   1
   X    ⎨  -0.90674608E+05 0.37861184E+09-0.93545751E+05 0.45230709E+09 0.10000000E+01*   1
        ⎩  -0.98871484E+05 0.33330994E+08-0.10772670E+06 0.47232786E+08 0.10000000E+01*   1
           SCALE FREQ               AXUNIT      1.0
           SCALE GAIN               PASSBAND    1.0
           END
LUS Rewind Flag  →  -7
                   -10
```

Table 1. SYSFIT Control Data File

1601

SC0) Control transfer card

1-6
SYSFIT
A6

The program control is transferred to Overlay 49 where the SYSFIT routines are located.

SC1) Logical unit assignment card

1-80
LU(I), I=1,20
20I4

LU(I) .EQ. 0 -- logical unit LU(I) will not be used in SYSFIT
LU(I) .GT. 0 -- logical unit LU(I) will be used and has been activated
LU(I) .LT. 0 -- logical unit LU(I) will be used but must first be activated

SC2) Case identification card

1-78	79-80
CASEID(I), I=1,14	
13A6	A2

SC3) Search Control Card

1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55
NV	NC	NEQ	NPF	MISR	MISCAN	MDG	MTRACK	NØFXCK	MTRMSR	MINPRT
11I5										

NV : The number of decision variables x to be read from cards following EPS (below). For EMTP cases there are no such cards, as x is loaded in accessory routine PSCAN.

NC : The number of explicit constraints upon x.

NEQ : The number of explicit equality constraints upon x.

NPF : The number of implicit constraints imposed via penalty functions.

MISR : The maximum number of iterations allowed for the optimization search process.

MISCAN : The maximum number of cases to be generated by accessory routine PSCAN.

MDG : The mode by which successive directions of search are generated. Values of 0, 1, 2 command Steepest Descent, PARTAN, and Conjugate Gradient search respectively.

TRACK : The level of printout for tracking the search process.

OFXCK : Supresses a numerical difference check upon the objective function gradient.

TRMSR : Commands the use of special search termination logic.

INPRT : Values from 1 to 3 provide increasing levels of printout supression.

C4) Search tolerance card

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
EPS
E15.8

Search is terminated when the projection of the objective-function radient onto the set of feasible x falls below EPS in magnitude. EPS s also used as a threshold for various other tests.

C5) Model specifications card

1 2 3 4 5	6 7 8 9 10	11 12 13 14 15	16 17 18 19 20	21 22 23 24 25	26 27 28 29 30	31 32 33 34 35
MPRNT	MFGTRK	MODEOX	NFITS	NOLINK	NORES	MDREFL
7I5						

MPRNT : Increasing positive values command increasingly detailed display of the model fit. Values through 2 produce display of final results only; greater values cause initial fitting details(prior to search) to be shown also.

FGTRK : Commands diagnostic printout from application routine FGVAL and routines subrordinate to it.

ODEOX : Default block mode (see later cards).

NFITS : The number of measurement paths to be simultaneously fit by the linear system model.

OLINK : A value greater than zero indicates that the model has no response paths to be linked together. PSCAN will otherwise expect a set of linkage operators and stack controls on the cards following.

NORES : A value greater than zero supresses calculation of residues for the fitted model.

MDREFL : Th mode for reflecting poles and zeros of the fitted m del into the left half of the complex plane.

SC6) Fitting specifications card

MDMØDE	LZSTEP	KTRIMO	KTRIMF	MØDEWT	MØDEF1	MØDEF2	NØWRAP
8I5							

MDMODE : Mode for loading measurement data.

LZSTEP : All data segments up to segment LZSTEP will be skipped over before measurements are loaded (from LUNIT8). Default value for LZSTEP is 1.

KTRIMO : The first KTRIMO frequency response measuremtns in the LUNIT8 segment to be loaded are discarded.

KTRIMF : Measurements KTRIMF through KMAX will be discarded.

MODEWT : If not equal to -2, MODEWT commands a redefinition of the fitting-error weights loaded from LUNIT8.

MODEF1 : Mode for fitting model gain to measured gain.

MODEF2 : Mode for fitting model phase to measured phase:

0 --- no fit
1 --- least-squares fit
2-4 --- time-delay adjustments, treated later

NOWRAP : Commands phase unwrapping. Not yet active.

SC7) Read-X control card

MXLXD	MXIXS
2I5	

MXLXD : Mode control for loading model parameter vector x. Negative values specify special operations such as LU5 rewind or case sequence termination:

-10 --- Last in current sequence of PSCAN-generated cases has been reached; return to SYSFIT main for new input (starting with a case identification card).

-8 --- This assumes that L3UF8 for the LUNIT8 data segment being processed is a general multiple of 7 (e.g. for transformation-matrix fitting). If an unprocessed "column" of this segment remains, then a pointer is advanced to it, LUNIT8 and LU5 are rewound, and control reverts to the main program.

-7 --- As for -8, but without pointer advancement or LUNIT8 rewind.

-6 --- First column of next LUNIT8 segment is processed, using the same initial value of X as for prior case.

-5 --- Present case is extended for another MISP search iterations.

-4 --- Commands special printout of model response, and requires input of frequency range data. Used to examine model behavior beyond the measurement range, or where measurements are poorly spaced.

MXLX8 : Positive value indicates read of commands for special constraints, after END card for last X array. A blank trailer card terminates the command sequence.

SC8) Path identification card

PATHID(I), I=1,14	
13A6	A2

SC9) Path-block limits card

NGBKS	NUBKS
2I5	

The model section being loaded consists of NPATHB = NGBKS + NUBKS locks, of which the first NGBKS blocks have general values of gain. he remaining NUBKS blocks have unity gain.

C10) LOCKX card

LOCKX(LXBASE+I), I=1,10
10I5

-1 --- Element X(LX) is initialized at the final value it achieved in the case just finished.
0 --- X(LX) is initialized at the value on the initial-X card (see below).
1 --- X(LX) is initialized and fixed at the value on the initial-X card.
N>1 --- X(LX) is held equal to X(N).

SC11) Initial-X data card

XBUF(I), I=1,5	SBO	MØDEX
5E15.8	A1	I4

XBUF : 5-element buffer for loading initial values into model parameter vector X. (see LOCKX card above).

SBO : Symbolic block operator, specifying how the block associated with XBUF links to those preceding it. For present EMTP applications the first block requires "=" and all others require "*", so that the model has all blocks in series.

MODEX : Specifies the mode by which X parametizes the current block. Present EMTP applications use only type 1 and type 9 blocks:

$$B(s) = \frac{x_5 s^2 - 2x_1 s + x_2}{s^2 - 2x_3 s + x_4}, \qquad (\text{MODEX} = 1)$$

$$B(s) = \exp(-x_5 s) \qquad (\text{MODEX} = 9)$$

SC12) Initial-X command card

The initial-X data cards must always be trailed by at least the END card shown in Table 1, to terminate the read loop. Intervening cards can be used to scale the block parameters just loaded, however. A partial list of commands is shown below, and will be discussed in a later section.

CBUF(1)	CBUF(2)		ØP1	ØP2	RSCALE		Format A
2A6		8X	A6	A4	E15.8		
CBUF(1)	CBUF(2)		ØP1	ØP2	MM	MDN	Format B
2A6		8X	A6	A4	3I5		

Examples:

```
SCALE FREQ                         0.037
SCALE FREQ          PASSBAND       1.0
SCALE FREQ          DATABASE       0.0
SCALE FREQ          AXUNIT
SCALE GAIN          FACTOR         3.28
SCALE GAIN          PASSBAND       1.0
CHANGE BLOCK TYPE                  3     *
CHANGE BLOCK TYPE   ALL
```

7.8.2 User Guidelines for "HAUER SETUP"

7.8.2.1 The wave propagation model

The propagation of each modal wave is represented by a linear dynamic model that consists of a pure time delay τ in series with a dynamic model for wave distortion. Desired frequency response for the model is specified by tabulated data derived from LINE CONSTANTS calculations. This is similar to a pure time delay followed by a low-pass filter with steadily accelerating rolloff (Figure 2).

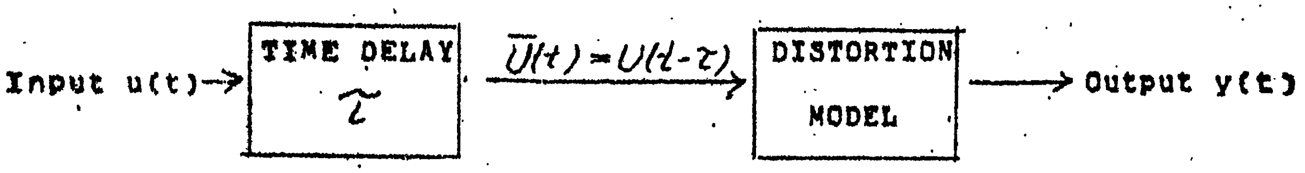


Figure 1. Model structure for wave propagation.

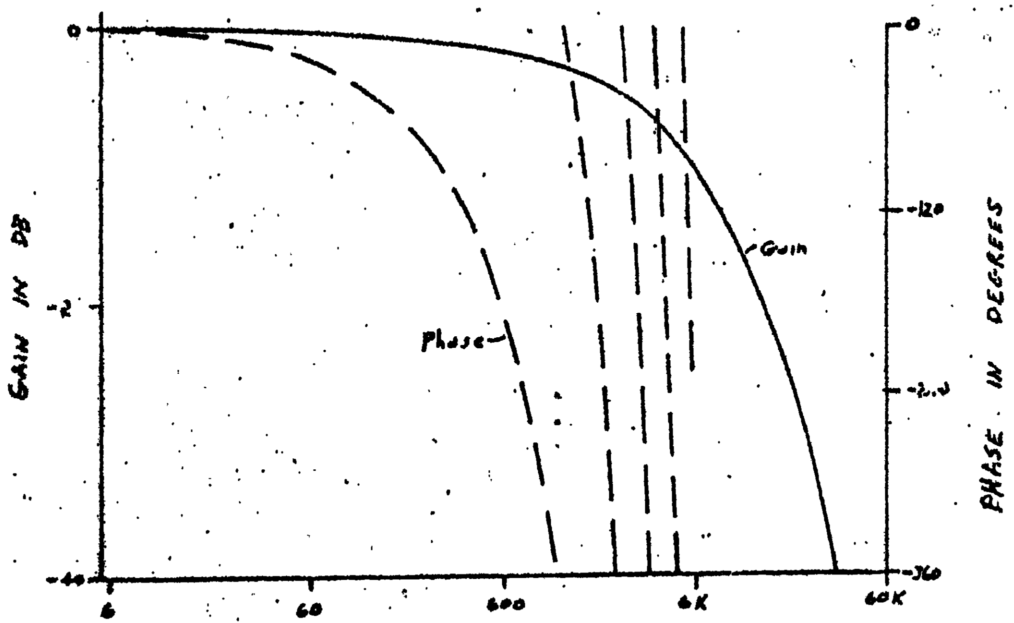


Figure 2. Typical gain and phase response for wave propagation.

The distortion model normally used consists of type-1 blocks in series, each with response

$$B(s) = \frac{x_5 s^2 - 2x_1 s + x_2}{s^2 - 2x_3 s + x_4} \qquad (1)$$

and with $x_2 = x_4$ enforced via LOCKX. This constraint assures that the model's step response will be unity for infinite time. Similarly, x_s is held zero for several blocks to assure that the time-domain step response will rise smoothly from zero.

After the model's parameter values have been found, its transfer function for distortion

$$T(s) = \frac{G\,(s - z_1) \cdot \cdot \cdot \cdot \cdot (s - z_m)}{(s - p_1) \cdot \cdot \cdot \cdot \cdot (s - p_n)} \tag{2}$$

is converted to the partial-fraction forms

$$T(s) = \sum_j \frac{K_j}{(s - p_j)} = \sum_j \frac{\hat{K}_j / p_j}{(s - p_j)} \tag{3}$$

Values of the poles p_j and step-response residues $\hat{K}_j$ are passed to the EMTP simulation routines, where they are used in the canonical state-space model provided for SEMLYEN SETUP.

7.8.2.2 Bandwidth Considerations

Model fitting is usually done out to the arbitrary data cutoff frequency f_{-40db}, where the response is 40 db down (i.e., 1%). This and several other critical bandwidths are printed out in Overlay 48, for each mode.

A general estimate of distortion-model risetime is obtained by the usual device of fitting a single-pole model to the 3 db bandwidth f_{-3db}, for which the time constant(the time to 63% rise) is

$$\hat{\tau}_{63\%} = \frac{1}{2\pi f_{-3db}} \tag{4}$$

Table 2 shows critical bandwidths for the Coulee-Raver double-circuit line. These indicate that some modes can respond thousands of times faster than others.

Mode	1	2	3	4	5	6
f_{-3db}	1.80	75	73	900	2000	1300
f_{-6db}	3.87	151	150	2640	6600	3800
f_{-40db}	35	2000	1700	83000	240000	110000

Table 2. Critical bandwidths for Coulee-Raver double circuit benchmark case, frequencies in KHZ.

For meaningful representation of wave distortion effects, the time step Δt must be small enough to capture a reasonable number of points on a wavefront. As a loose rule of thumb, I propose that Δt be not greater than half the value of $\hat{\tau}_{63\%}$ for the fastest mode of interest, and preferably several times smaller. Means for pruning off the modes that are too fast for a given Δt are discussed later.

7.8.2.3 The Characteristic Admittance Model

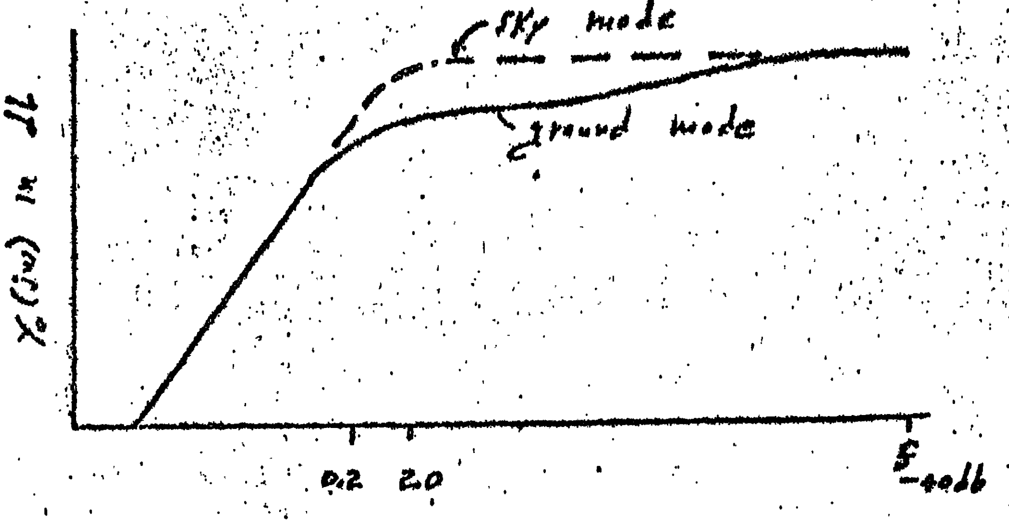


Figure 3. Typical Y_o response

The modal characteristic admittance is given by

$$Y_o(s) = \left(\frac{G + CS}{R + LS} \right)^{1/2} \tag{5}$$

where R, L, G, C will vary with s in realistic cases. For G=0, the low-frequency response is approximately

$$Y_o(jW) = \left(\frac{jWC}{R + jWL} \right)^{1/2} \tag{6}$$

Thus Y_o exhibits an initial $\sqrt{f}$ behavior, with a phase of 45 degrees. A corner of "knee" occurs somewhere near 0.2 Hz for the earth return mode (mode 1), and near 2-5 Hz for the upper modes. The upper modes often have Y_o constant above 10 Hz, for all practical purposes. For mode 1, however, Y_o may roughly double between 10 Hz and f_{-40db}, and may show mild oscillations.

It should not be necessary to model Y_o above f_{-40db}, as the wave propagation is so weak there that very little line activity would be found in normal cases. In like manner, some cases do not require close modeling at frequencies below the knee. Exceptions should be anticipated when the line has system-frequency initial conditions, or when a very low frequency AC model is used to approximate a DC system.

The standard model now in use for Y_o assumes that leakage conductance G in (5) is zero, and uses an initial type -1 block in form

$$B(s) \frac{x_5 s^2}{s^2 - 2x_3 s} \qquad \frac{x_5 s}{s - 2x_3} \tag{7}$$

conditions $x_1 = x_2 = x_4 = 0$ are enforced through LOCKX. The remaining blocks are in series with the first, and are type 1 with gain held at unity but all other parameters free. Thus the model has as many zeros as poles, and its frequency response will approach a constant with increasing f. Use of (7) "anchors" model response at zero for $f = 0$. Achieving a $\sqrt{f}$ characteristic from there to the response knee requires a number of poles and zeros on that frequency range, however, and should not be attempted unless special circumstances require it.

7.8.2.4 Model Scaling

In normal EMTP applications SYSFIT will perform at least one model-scaling operation. The first of these is commanded by a positive value for MOCI(3) in the frequency response data header, set automatically in OVERLAY 48. It consists simply of dividing each measurement frequency by AXUNIT, where AXUNIT is of form 10^N and N is selected so that the maximum scaled frequency lies between 1.0 and 9.999... A corresponding scaling of initial X is obtained by the command "SCALE FREQ AXUNIT" in Table 1.

Initial X for the wave propagation model is normally scaled so that model response roughly matches specifications at the bandpass frequency, which at present is defined as f_{-6db}. To this end a standard value of X is provided, for which model response is down 6 db at 1 Hz. This value is frequency-scaled to match the data in response to the command "SCALE FREQ PASSBAND".

Final X is usually saved on LU10, so that a successful fit [illegible] not be repeated or so that a tentative fit can be continued. This [illegible] is already scaled by AXUNIT. If it is copied into the SYSFIT command data file all SCALE commands should be removed, as should be the "-7" rewind flag for LU5. In this situation a distinct card set, similar to Tabel 1 but without the LU assignments card or the -7 flag, should be used for each mode.

7.8.2.5 Criteria For A Good Model Fit

Unless the user is applying SYSFIT in very familiar situations, printout of fitting results should be allowed and these results should be reviewed.

A general indication of the quality of fit is provided in the printer plots labeled GAIN FIT and PHASE FIT, where * denotes model response and X denotes measurement data (from LINE CONSTANTS). Gain and phase error are shown as EPS T2 and EPS TH on the FIT ERROR plot; these too are in db and degrees. A good fit to wave propagation will have a gain error within a few tenth's of a db(0.1 db = 1.16%) over most of the frequency range, with larger values possibly occuring near f_{-6db}. Phase error will not usually exceed 10 degrees, for mode 1. The upper modes, having greater bandwidth, are fit less well by a 14-pole model and in some cases may have gain errors in the 0.5 - 1.0 db range. This is probably acceptable, as these modes are usually much faster than the processes under study.

A close gain fit at steady-state frequency f_o is commanded by a positive value of KPS on the "HAUER SETUP" misc. data card, and usually produces an error of less than 0.01 db for both the wave model and the admittance model. Exact phase fitting at f_o for the wave model requires the additional use of MODEF2 4 on the fitting specifications card. This is achieved by adjusting τ, and so does not apply to the admittance model. Use of MODEF2 = 1 for the latter will produce phase fitting at all frequencies, with the fit at f_o weighted heavily. This option is somewhat expensive computationally, and in theory at least may introduce convergence problems (due to present lack of phase-unwrapping logic). The erudite user who encounters this situation will first fit on gain alone, and then continue the fit using MODEF2 = 1. An automatic program feature for this will be provided later.

Just prior to the printer plots, block pole/zero locations are printed out in both scaled radian frequency and true frequency. This printout should be examined for poles or zeros far off the measurement frequency range, which would be an abnormal and possibly hazardous condition for the wave model. For the admittance model it is not uncommon, and seems to make no difficulties provided that the poles are real or at least well damped.

Residues K_ℓ and $\hat{K}_\ell$ are printed after the pole/zero locations. The high-bandwidth modes sometimes encounter a "small differences of large number" problem with the K_ℓ, for which $\hat{K}_\ell$ usually exceeds 10^5. (altering data conventions to pass K_ℓ rather than $\hat{K}_\ell$ would make this condition more visible). The normal remedy is to allow more search iterations. Use of a lower-order model (say 6 poles) is more economical, however, and is an appropriate means for approximating a mode that is too fast to warrant detailed modeling. Starting data can be obtained by changing NGBKS to 4 in the wave model of Table 1, and then using the first half of the card sets for LOCKX and X.

7 8.2.6 Rules of Thumb

A) The exponential scan of frequency response should start one decade below system frequency (e.g., at 5 or 6 Hz) and extend upward for about 10 decades to assure that $f_{-40 db}$ is located for each mode.

B) If initialization or sustained performance at f_0 is required, use KPS=1 and KYC=0 in the misc. data card of "HAUER SETUP". Set MODEF2=2 for the wave model, MODEF2=0 for the admittance model. Otherwise set KPS=0, and MODEF2=2 for the wave model.

C) Printout from Overlay 48 provides bandwidth estimates and risetimes for the wave distortion model, and the change in admittance magnitude from the starting frequency out to $f_{-40 db}$. This may reveal that certain modes are too fast to justify close wave modeling, or that their characteristic admittance is essentially fixed. (A preliminary run through SYSFIT, but without optimization, can be useful in verifying this).

D) If some modes require special treatment, such as reduced model order, expand the data of Tables 1 (or a replacement) to represent each mode individually, and remove the -7 card. Otherwise the file can be used directly. For some purposes the "default" fit obtained without optimization is adequate. Normally 150-300 iterations are needed to assure tight fitting, especially if KPS=1.

E) After initial fitting is done, expand the SYSFIT control data to represent each mode individually and copy in final K values from the LU10 file. Redefine search controls appropriately, so that a completed search is not needlessly continued later. Continue the fitting with another run, if needed.

8. "TACS" —— A DIGITALLY-SIMULATED ANALOG COMPUTER (DIFFERENTIAL ANALYZER)

"TACS" is an acronym for Transient Analysis of Control Systems, an EMTP mod ling capability which grew out of Laurent Dube's doctoral research (which was conducted under Prof. Hermann Dommel of the University of British Columbia in Vancouver, B.C., Canada). Several EMTP memoranda have dealt with this development (see Ref. 8,

But perhaps the best introduction to the idea of TACS is provided by the 1977 IEEE PES PICA paper which has been written by Laurent and Hermann (Ref. 12), a copy of which is reproduced below. User instructions will follow this overview.

SIMULATION OF CONTROL SYSTEMS IN
AN ELECTROMAGNETIC TRANSIENTS PROGRAM WITH TACS

L. Dubé, Student Member, IEEE

H.W. Dommel, Member, IEEE

ABSTRACT

A program "TACS" (Transient Analysis of Control Sys-tems) has been developed for simulating the dynamic interactions between control systems and electric net-work components represented in a transients program. Control systems can be described in the usual form of block diagrams with arbitrary configurations of various basic elements, functions and devices. TACS solves the control system equations in the time domain by implicit integration with the trapezoidal rule. It has been successfully used for simulating the transient behav-iour of HVDC converter stations with their controls and connected lines, transformers and other components on the dc and ac side. TACS has also been used for simu-lating excitation systems in network studies with de-tailed representation of synchronous generators.

INTRODUCTION

In attempting to include HVDC converter models into the Electromagnetic Transients Program (EMTP) of the Bonneville Power Administration, it soon became appa-rent that the main effort had to be devoted to the simulation of the HVDC converter controls. The con-verter valves themselves could be modelled very simply as switches, with closing controlled by firing signals and opening taking place at current zero. The simu-lation of the converter controls was less obvious, pri-marily because of substantial differences among various converter control schemes. It was felt that the best way to keep the program flexible was to design a con-trol system simulation package which could accept any arbitrary interconnection of a set of control system building blocks, and to interface this package with EMTP. This led to the development of TACS described here, which has found many applications far beyond HVDC converter models for which it was originally conceived.

I. THE TACS PROGRAM

Control systems are generally represented by block diagrams which show the interconnections among various system elements, such as transfer function, gains, limiters, algebraic and logical functions, and other special-application devices. Fig. 1 is a typical example. A block diagram representation has also been chosen for presenting data to the TACS program because it makes d ta preparation very simple. Before punching data cards, all the program user has to do is to assign six-char cter alphanumeric names to all signals of the system, as indicated in Fig. 1. The elements of the control system are then easily specified on cards with a set of formats for the various types. Simulation r sults show the printed or plotted time response of selected system signals.

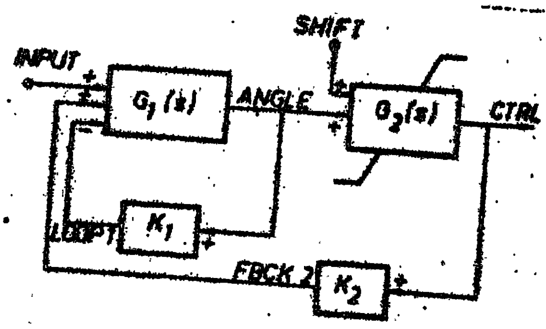


Fig. 1. Typical block diagram representation of a control system.

Basic Elements

Some elements or "blocks" appear in most control systems. They are handled in TACS in the following way:

The transfer function or 's-block' is used to describe a multiple-input/single-output transformation of arbitrary order in s of the form $G(s) = N(s)/D(s)$ with optional dc gain, where $N(s)$ and $D(s)$ are m-th and n-th order polynomials of s with $m \leq n$ (see Fig. 2).

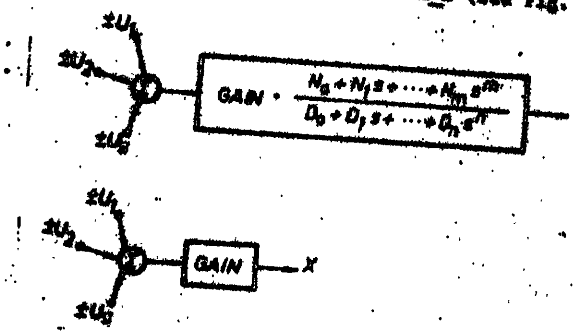


Fig. 2. Basic components of a control system.

The operator s can be thought of as either the Laplace variable or as the d/dt operator. The program converts the polynomial coefficients N_i, D_i of the s-domain to coefficients of a transition relationship in the time domain as explained in section II.

The 'zero-order block' is used to describe a lin-ear relation between the output of a block and the sum of its inputs (see Fig. 2). This element is mainly used for simple summators, and f r potentiometer or am-plifier settings.

The limiter imposes low and/or high limits of assigned or computed value on any transfer function block or zero-order block (see Fig. 3).

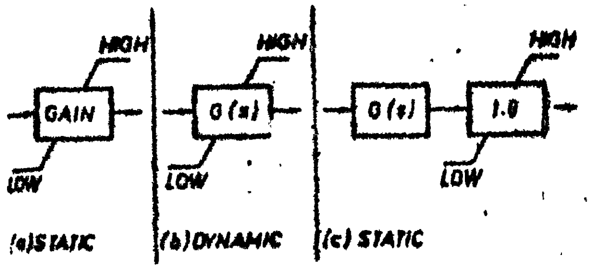


Fig. 3. Static and dynamic limiters.

With the 'static' limiter, the output value of the zero-order block is simply clipped to the limit value whenever the latter would have been exceeded otherwise. The output value of an s-block with 'dynamic limiter' is calculated differently, however, depending on whether the block is operating inside or outside its defined limits. In the latter case, the first and higher order derivatives of the output are set to zero and the structure of the equations is changed. Whether a limiter is static or dynamic depends on how the physical system actually works. For example, a limiter is dynamic if the complex-impedance feedback loop of an amplifier is electrically modified or by-passed whenever a limit is reached.

Algebraic, Transcendental and Logical Function Blocks

In addition to the preceding elements, the program also accepts blocks with algebraic and transcendental functions, and with logical operators (Fig. 4). Simpler elements - such as multipliers and dividers - can be directly represented by their corresponding algebraic operators (+, -, *, /, **). Functions of a more complex form are specified with FORTRAN function names. Most functions of the FORTRAN Function Library are permitted. Such functions may be inserted in any part of the control system. Series of functions may be cascaded, and will be solved sequentially in the order defined by the user.

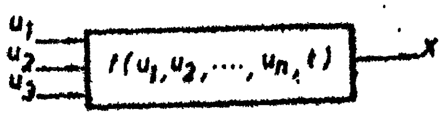


Fig. 4. Algebraic and logical functions.

The user can also define logical signals and functions of logical signals. A set of logical operators is provided (.G., .AND., .NOR., etc.), which may be used in conjunction with any other element of the system (including relays, transport delays, time-controlled switches) for representing the logical section of a control system. As with the other blocks of the representation, the interconnection of the logical signals is totally arbitrary, and is left to the user. All transfer function blocks and algebraic and transcendental function blocks are fully compatible with the logical signal blocks.

Special-Application Devices

Control systems often contain devices of a special design, such as special-purpose transducers. The present version of the TACS program accepts the following devices, which frequently appear in power network studies:

frequency sensor, to monitor the frequency of periodic signals;

relay-operated switch, for which the driving signal may be any of the system signals;

level-triggered switch, which provides a simple level detector;

transport delay block, simulating transmission delays over remote sections of a system (this requires storage of the input signal as a function of time);

pulse transport delay, for imposing variable delays on logical control signals (this requires a counter only, in contrast to the storage scheme of the preceding delay block);

digitizer, for level-sampling of analog signals;

user-defined nonlinear functions, given as x-y coordinates of saturation characteristics and other nonlinear one-to-one transformations;

time-controlled switch, for changes in the system topology at specified instants of time.

Just like other blocks of the system, these devices are simply defined by the alphanumeric name of their output signal, and the names of the previously-defined input signals on which they operate.

A straightforward procedure permits the user to define special-application devices not contained in the above list through user-supplied FORTRAN subroutines. Because of the variable-dimensioning structure of the program, increasing the potential size of arrays does not require recompilation, since any global and local dimension can be re-defined at execution time.

Signal Sources

The control system is excited by means of independent input signals which are called signal sources or generators. Each source is defined on a single card as a separate system component. Once declared, these signals can be used as input to any other block in the system. Activation and de-activation times, before and after which the sources become zero, can be arbitrarily specified by the user.

Because of their frequent use, the two following types of sources are built into the program:

dc signals, including step and pulse functions;

sinusoidal signals with user-defined amplitude, frequency and phase.

Two other, frequently used sources are always available without having to be declared explicitly, namely the signal source 'unity' and the simulation time t in seconds.

Finally, as explained in section III, variables such as node voltages, branch currents and switch status are also available as input signals through the interface with the EMTP in studies of power network transients. Similarly, all voltage and current sources built into the EMTP can be used directly as sources in the TACS program.

II. SOLUTION METHOD

Solution of Linear Equations

Before entering the time-step loop, all transfer functions in the s-domain are converted into algebraic difference equations in the time domain with a multi-order version of implicit integration with the trapezoidal rule. In effect, the n-th order transfer function is rewritten as a system of first-order differential equations, which are integrated with the trapezoidal rule. The internally created state variables for second and higher order derivatives of input and output variables are then eliminated, which produces a single equation

$$c_0 x(t) = d_0 u(t) + HIST_1(t-\Delta t), \qquad (1)$$

where u is the sum of all input variables. There are n "history terms" which must be updated in each time step after the solution has been found at t,

$$HIST_1(t) = d_1 u(t) - c_1 x(t) - HIST_1(t-\Delta t) + HIST_2(t-\Delta t)$$
$$\vdots$$
$$HIST_i(t) = d_i u(t) - c_i x(t) - HIST_i(t-\Delta t) + HIST_{i+1}(t-\Delta t)$$
$$\vdots$$
$$HIST_n(t) = d_n u(t) - c_n x(t) \qquad (2)$$

The coefficients c_i, d_i are calculated once at the beginning from the coefficients N_i, D_i of the polynomials in the transfer function (see Fig. 2), with recursive formulas, e.g., for d_i:

$$d_i = d_{i-1} + (-2)^i \left[\binom{i}{i} M_i + \binom{i+1}{i} M_{i+1} \dots + \binom{n}{i} M_n \right],$$

where $\binom{i}{j}$ = binomial coefficients, (3)

$$M_i = (2/\Delta t)^i N_i,$$

$$d_{-1} = 0$$

Zero-order function blocks can be translated directly into linear algebraic equations (without history terms). Combining these equations with (1) results in a system of linear algebraic equations of the form

$$\sum_j a_{ij} x_j(t) = b_i \qquad (4)$$

which completely describes the linear part of the control system, even in the presence of looped configurations. The repeated simultaneous solution of (4) with constant coefficients a_{ij}, gives the response of all linear variables in the time domain over successive intervals Δt. The right-hand sides b_i change from step to step and are primarily made up of past-history terms (2), which must be updated after each time step.

Equations (4) are solved as follows: Before entering the time-step loop, triangular factorization is applied to the A-matrix, Fig. 5.
The unknown variables are then found in each time step by a forward solution on the right-hand sides b_i, followed by back substitution to obtain the system variables x_i. Ordering techniques are used to minimize the number of fill-ins in the triangularization, to keep the number of operations in the time-step loop as low as possible and, together with a sparsity storage scheme, to reduce the size of the memory for storing the triangularized matrix.

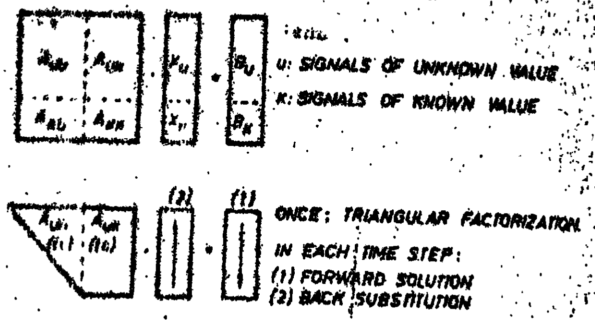
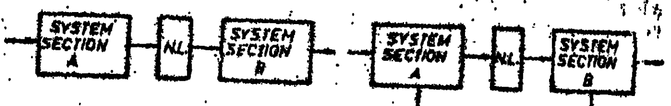


Fig. 5. Simultaneous solution of linear algebraic equations.

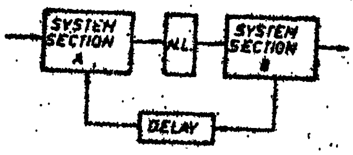
Nonlinear Functions

Nonlinear function blocks are not directly included in the simultaneous solution of (4). Their respective output signals are evaluated sequentially as soon as their input signals become available at some stage in the back substitution (Fig. 5).

If nonlinearities were to appear only in open-loop configurations (see Fig. 6a), the approach just described would provide a truly simultaneous solution of the complete system as long as the variables are ordered in such a way that those of section A are found first before those of Section B. But nonlinear functions are often inside closed-loop configurations (Fig. 6b), which prevents a true simultaneous solution of all system variables in one pass with the described approach.



(a) OPEN-LOOP CONFIGURATION (b) CLOSED-LOOP CONFIGURATION



(c) UNCOUPLING OF THE SOLUTION

Fig. 6. Treatment of nonlinear functions (N.L. = nonlinearity).

Two options are available to overcome this difficulty. The straightforward approach is to linearize the nonlinear functions around the approximate solution point with a Jacobian matrix, and to solve the system of equations repeatedly in an iteration loop. This is c stly, however, because it requires re-triangularization of the matrix in each iteration step, or at least from time to time, depending on the type of non-linearity. Due to the interface application of this program with EMTP, a different approach seemed desirable, which could easily be implemented precisely because of the particular type of application. This approach use uncoupling of the feedback paths across the nonlinear functions as shown in Fig. 6c.

In typical transient studies, the size of the time step is dictated by the power network components, for which the time constants of interest are normally much smaller than the time constants of the associated control systems. Typical values for time steps in the simulation of power network transients lie between 10 and 200us. This interval is normally very small for the control system simulation, which makes it possible to insert delay elements of one time step duration into the control system with little or no effect on the results.

Although such delay elements can be inserted explicitly by the user, the program will automatically impose a delay of one time step whenever a loop with a nonlinear block must be broken. The program does this indirectly by evaluating the nonlinear function output from input values of the preceding time step. The value of a nonlinear function output is thus prevented from having an immediate effect on the input signals of the same function.

Dynamic limiters create a special type of nonlinearity. When a limit is reached, the derivatives of the output are set to zero, which changes the structure of the differential equations. This requires reformulation of (4) and re-triangularization of the matrix whenever the output hits the limit or backs off the limit again. Instead of actually changing the matrix, the effects of the changes can also be included into the right-hand sides with the compensation method [3], as long as only a few dynamic limiters are at the limit simultaneously.

Initial Conditions

The solution of the system equations includes the calculation of the history terms in (2). These history terms must be initialized at t=0 before the time-step loop is entered. To calculate these initial conditions the values of the inputs and output of all s-blocks and transport delay blocks must be known at t=0.

As a rule, the system is assumed to be operating in steady state for $t \leq 0$. Although the user has the option of specifying his own set of initial conditions, the program will normally calculate the necessary dc and ac steady-state solutions whenever dc or ac signal sources are specified as active during steady state (for $t \leq 0$). However, dc initial conditions of integrator outputs must always be provided by the user, since they are undefined in dc steady-state operation. The dc and ac solutions of the linear components are calculated separately, and then superimposed to provide the correct initial conditions of system variables and history terms. In the present version of the program, the ac steady-state solution is only performed for a single source frequency, although solutions at more than one frequency could b superimposed to the basic signals.

III. APPLICATION TO POWER NETWORK TRANSIENTS

The TACS program described in the first two sections of this paper has been interfaced with the Electromagnetic Transients Program (EMTP) of the Bonneville Power Administration. By using the TACS and EMTP programs together, it becomes possible to analyze the dynamic interaction between electric network components modelled in EMTP and the associated control systems modelled in TACS. This increases the versatility of transient simulations considerably, as explained below.

Power Network Representation

The power network is simulated with the transients program EMTP of the Bonneville Power Administration, which has been described in detail before [2,4]. Only a brief summary of its features is given here. Before punching cards for the input data, the user must first assign alphanumeric names to the nodes in the network diagram, which are then used to identify the branch, switch and source data. The following branch types are provided: Series connection of lumped elements R,L,C, single- and multiphase π-circuit, single- and multiphase distributed parameter line with constant parameters, distributed parameter line with frequency-dependent parameters, transformer model, nonlinear inductance, nonlinear resistance, and some other types. Switch models are provided for the simulation of circuit breaker poles, of protective gaps and of valves in HVDC converter stations. The valve switch is a new feature which has been added when EMTP was interfaced with TACS. Voltage and current sources can be specified at any number of nodes. The program can start from any specified ac steady-state conditions, which are automatically computed by a subroutine, with nonlinearities either linearized or ignored.

Description of the Interface

The electric network and the control system are solved separately in the EMTP and TACS programs t each time step. However, variables from one program can be passed to the other program (see Fig. 7).

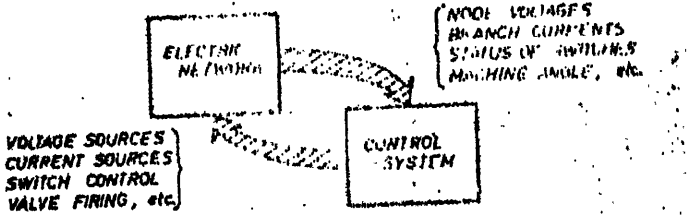


Fig. 7. Dynamic interaction between electric network and control system.

As external input signal sources, the TACS program will accept the value of node voltages, branch currents, switch status, or other variables defined in the electric network. In turn, any signal of the control system may be passed to the electric network as a voltage or current source, as a converter valve firing signal, or as a switch operating signal.

At each time step of the simulation, the evaluation of the control variables in TACS follows the evaluation of the electric variables in EMTP. This sequence implies a delay of one time step in the application of control signals to the electric system. Modelling inaccuracies introduced by this delay, which is typically in the order of 10 to 200µs, are normally negligible in the electric system..

The steady-state initialization of each system is also done separately at this time, which is probably acceptable for most types of studies. If separate solutions turn out to be inadequate in the future, then iterative solutions would have to be developed for the steady-state initialization of the combined systems. Since the steady-state solution of the electric network is calculated first now, any variable from the electric network is automatically available for the initialization of the control system. Conversely, the user needs only define initial conditions for control signals that are required for the initialization of the electric network.

Application to HVDC Converter Stations

The interfaced execution of the TACS and EMTP programs allows the user to model any configuration of HVDC converter valves with their associated valve firing and protection control systems. The simulation will show the transients on both the ac and dc side of the system. Interactions among transients on both sides and the behaviour of the control system under transient conditions can therefore be easily studied. The user may choose detailed representations for part of the system, and use simpler models for other parts of the system. Because of the arbitrariness of the configurations, the user can easily include the representation of by-pass valves and of other network protection schemes. The various configurations of multiterminal HVDC transmission systems can also be readily represented, along with the operation of telecommunication links used for both control and monitoring purposes.

Studies using the present version of the program for the simulation of transients in the HVDC Pacific Intertie are now under way, and the results will be reported when available, along with an evaluation of the adequacy of the present valve representation as controlled switches in the EMTP program.

Application to Excitation Control

The TACS program has been used in combination with a synchronous generator model, which was incorporated into the EMTP program at Southern California Edison Co. In studies of sub-synchronous resonance, TACS was used to represent the excitation systems of the generators. Because control systems are user-defined in TACS, any of the IEEEstandard excitation system models can be readily represented. The values of terminal voltage, generator rotor angle, speed change, bus current, and network frequency are monitored in EMTP and used as input signals to the excitation systems, while the values of the exciter voltage are fed back to the generator model equations in the EMTP program.

Other Applications

From the description of the various TACS elements and functions, it should be clear that the program can be used to simulate many other network components or phenomena. The following examples illustrate some possible applications:

- Studies of the transient behaviour of monitoring equipment and protection devices in power networks in response to transient conditions determined by the EMTP program.
- Studies of thermal behaviour and temperature monitoring in power network components during transients determined by the EMTP program, with feedback from TACS to EMTP in cases where the thermal behaviour changes the electric characteristics (e.g., thermal behaviour of semiconductor valves, of circuit breakers, or of surge arresters).
- Representation of inverter-fed induction machines with valves and machines simulated in the EMTP, and the control elements simulated in TACS.
- Analysis of transients in rectifier-fed dc motors, in applications such as mill drives and electric railways.
- Simulation of various controlled network components, such as synchronous condensers, saturated-core reactors, etc.
- Representation of equivalent models of sources or loads in power network simulations (including current- or voltage-controlled sources) that may be used in TRV studies, or for simplified representations of HVDC converter stations, etc.

The wide range of possible applications results from complete flexibility in the configurations for both the electric components and the control functions. It is hoped that experience gained by others in the use of these combined programs will be reported.

CONCLUSIONS

A general-purpose program for the transient analysis of control systems (TACS) has been developed which can be interfaced with an electromagnetic transients program to simulate the control system part of power system components. It has been written to make its use as flexibile as possible. While TACS was originally conceived for the simulation of HVDC valve firing circuits, it can be used for a wide range of other applications as well.

Acknowledgements

The TACS program has been implemented in the BPA EMTP program in close collaboration with Dr. W. Scott Meyer and Dr. John J. Vithayathil of the Bonneville Power Administration.

Mr. Michael C. Hall, of the Southern California Edison Co., has contributed to using TACS for simulating synchronous generator excitation systems.

Preliminary studies hav been conducted under Scholarship Sch-248 from the National Research Council f Canada.

rences

TACS User's Guide, Bonneville Power Administration, Branch of System Engineering, Portland, Oregon, August 1976.

H.W. Dommel, "Digital Computer Solution of Electromagnetic Transients in Single- and Multiphase Networks." IEEE Trans. Power App. Syst., vol. PAS-88, April 1969, pp. 388-399.

[3] W.F. Tinney, "Compensation Methods for Network Solutions by Optimally Ordered Triangular Factorization." IEEE Trans. Power App. Syst., vol. PAS-91, Jan./Feb. 1972, pp. 123-127.

[4] H.W. Dommel and W.S. Meyer, "Computation of Electromagnetic Transients." Proc. IEEE, vol.62, July 1974, pp. 983-993.

Note: Reference 1 above no longer exists as a separate entity. This material is now an integral part of the EMTP User's Manual, particularly the present Section 8. The bulk of this documentation was written by Laurent, as part of his contract with BPA.

The present section of the EMTP User's Manual contains the full set of rules associated with the definition of the TACS data cards. See also Sections 1.0g2 and 1.1d for the accompanying special-request cards.

8.1 Purpose of TACS
8.2 Summary of TACS capabilities
8.3 How to simulate what
8.4 TACS steady-state initialization
8.5 TACS elements, card formats

8.1 Purpose of TACS

TACS has been designed for use as a simulation tool functionning in ways similar to analog computers, differential analysers, and algebraic and logical processors combined.

Also, TACS signals and EMTP electrical-network variables can be interfaced, forming a hybrid EMTP-TACS interactive configuration.

Typical applications of TACS are:

- simulation of HVDC Converter controls
- simulation of synchronous machine excitation controls
- implementation of special-purpose TACS-controlled switches in the EMTP
- representation of flexible source and load characteristics in the EMTP.

Not all avenues of the utilization of TACS and its interface with the EMTP have yet been explored, and the user's curiosity and inventiveness in experimenting with these features are highly encouraged.

8.2 Summary of TACS capabilities

The TACS program is used to solve the differential and algebraic equations associated with an arbitrary interconnection of the following elements:

- transfer functions in "s", of any order;

$$\text{OUTPUT} = \text{GAIN} * \text{Sum}(\text{inputs}) * G(s)$$

- order-zero blocks;

$$\text{OUTPUT} = \text{GAIN} * \text{Sum}(\text{inputs})$$

- limiters (saturation), static or dynamic (with or without windup), with constant or variable limit values, superimposed on the transfer functions and order-zero blocks;
- input signal sources, such as level, pulse and step functions, sinusoidal signals, any node voltage, switch current or switch status as measured in the electrical network, and others;
- supplemental algebraic and logical variables, using the standard algebraic and logical operators and all functions of the FORTRAN library;
- special-application devices, such as frequency meter, relay, level-trigger, transport delay, pulse delay, digitizer, point-by-point user-defined non-linearity, time-sequenced switch, controlled integrator, simple derivative, input-IF component, signal selector, sample and track, instantaneous min/max, min/max tracking, accumulator and counter.

In addition, any signal among these elements can be passed to the electrical network as a voltage or current source, or as a signal controlling the operation of a switch, valve or diode.

Program output (printed and/or plotted) consists of values of the block-output signals as a function of time, for those variables requested by the user.

Both global allocation and internal distribution of the number of memory cells required for the storage of the TACS arrays are variable and user-defined. (See Section 0.6)

8.3 How to simulate what

While designing TACS, all efforts have been made to permit the translation of a case, from its physical description to a series of data cards, to be as straightforward as possible. (Any deviation from this principle should be promptly pointed out to Program Maintenance.)

Here are the basic rules which must be followed when the user is preparing the data for a simulation.

Requirement 1.

The control circuitry whose behavior is to be simulated must be first described as a block diagram, showing the interconnections

(with sign and direction) between all blocks and signal sources. Recognizable blocks are as detailed elsewhere in this Section, transfer functions, order-zero blocks, limiters, algebraic functions and logical operators, and a series of other special-purpose devices.

This type of description (blocks and arrows) has been chosen because it is very close to the form in which control systems are generally represented for purposes of design and analysis. (See Sect. 1.)

Requirement 2.

Each block and signal source must then be assigned a single output, which must be "named" in a way that will unequivocally identify it among the other blocks of the setup. The name itself can be any arbitrary mnemonic code, and it is the user's prerogative to choose an adequate level of confusion in this naming process. These names will later be used to directly identify the interconnections between the blocks. A name is any sequence of 1 to 6 alphanumeric characters, including blanks. (See Section 1.)

Requirement 3.

The user must then assemble the data according to the rules set for the different types of blocks and devices. It is suggested at this point that the user get acquainted with the technicalities of the TACS data setup by preparing and running a few simple cases at first. This method of self-teaching has proven to give positive results in getting the user to gain flexibility in dealing with the constraints of the program, ability to see the file of time-domain simulation in a more realistic perspective, and familiarization with the typical gumption-traps which could make the preparation of a case to be more annoying than expected for overconfident users.

In summary:

- use block diagram representation to describe the system
- name all variables
- define the data in the specified formats .

8.3.1 Assembling the data for a simulation run

In order to simulate a particular control system, the user must prepare a symbolic description of the system. This setup will be referred to as the TACS data deck. The data deck consists of the following groups of cards, in the given order. (See Section 8.5)

Note: Comment cards (with a "C" in column 1) may be embedded anywhere and in any number in the data deck.

FUNCTIONS (s-blocks, z blocks, limiters)

SOURCES (internal & interfaced signals)

SUPPLEMENTAL < VARIABLES
DEVICES

Program OUTPUT Specifications

Initial conditions (optional)

8.3.2 Ordering of the blocks

At execution time, when the TACS program calculates the value of each variable of the system for a particular instant of time, it does so in a specific (and sensible) sequence. This sequence is shown in the table below. In most applications, the user does not need to worry about this sequence of the solution (the program does the proper sequencing itself) . But knowledge of the sequence may be used to entangle some tricky situations involving non-linearities such as the limiters and the supplemental "inside" variables and devices.

All linear variables (transfer functions and order-zero blocks) are solved as one group, by triangularization and backward substitution,[3] thus providing a "simultaneous" solution of all such variables, even in the so-called "looped" configurations.

Supplemental variables and devices are separated in three supplemental groups (input, output and inside) . The variables of each group are solved sequentially within each group, in the order in which the data cards were read in.

Order in which the FACS variables are calculated

1. Sources, sequentially, as read in.
2. Suppl. "input" variables/devices, sequentially as read in.
3. Delay s-block functions and pure integrators.
4. Z-blocks with limits, which are input to suppl. "inside" var./dev.
5. S-blocks " " " " " " " " "
6. Z-blocks without limits, " " " " " " "
7. S-blocks " " " " " " " " "
8. Suppl. "inside" var./dev., sequentially as read in.
9. Z-blocks with limits, other than 4,
10. S-blocks " " " " 5.
11. Z-blocks without limits, other than 6.
12. S-blocks " " " " " 7., with more than 2 inputs.
13. " " " " " " , with only 2 inputs.
14. " " " " " " , with only 1 input.
15. Suppl. "output" var./dev., sequentially as read in.

When the block diagram is converted to data cards, it can be seen :om the above list that the user will try to minimize the number of ipplemental "inside" variables/devices, by defining them as either :nput" ones or "output" ones as much as possible. The reason for this ncern is to preserve as much as possible the "simultaneity" of the lution. Whenever an "inside" supplemental var./dev. is part of "loop", the simultaneity is broken (try it by hand calculations...), d the solution automatically inserts a delay of one time-step at some int within this loop. (Note: if the user is interested in knowing th certainty where this delay will appear, it is suggested that he sert a delay-block himself, thus decoupling the non-linearity an explicit way.) (See "Solution Method, Nonlinear Functions", p.276)

The above list may also be useful in determining whether a imed" limit is actually evaluated before the limit is applied is should be), or after (in which case a delay of one time-step ects the application of the limit to the block output).

Finally, one advice about the order in which the z-blocks and s-blocks are specified (as given by the sequencing of the data ds). If the user defines those blocks in the direction opposite the flow of the signals (backwards), a minimum number of itional terms will be created by the triangularization process, consequently the user can save on storage requirements. user should ignore this advice for small cases, when storage space of no concern. On some larger cases, this simple trick might ve useful in preventing the unnecessary re-dimensioning of the es by the user.

8.4 TACS Steady-State Initialization Rules

Point 1.

Why bother with the definition and calculation of initial conditions in TACS ?

a) All history terms must be initialized before the program is ready to calculate the solution of the system at the first time step. For this purpose, the program will need the values of the inputs and the output at $t = 0.0$ of all s-blocks and of devices type 53 , 58 , 59 , 62 , 64 , and 65 .

b) The variables requested for output (printed and/or plotted) should have correct values for the time $t = 0.$.

Point 2.

The program will automatically calculate the dc steady-state output values of certain types of blocks (read on), while the user must provide "user-defined initial conditions" for the others. However, the program does not need (and will not calculate) any dc steady-state output values, unless there is one or more type -1, -92 and -93 sources connected at time $t = 0.$ and active in steady-state (as indicated by a value of T-START $< 0.$) .

Point 3.

When TACS does calculate its own dc steady-state output values,

a) the program will take care of computing output values for all order-zero blocks and all s-blocks (transfer function blocks), except: - integrators $[\ G(s) = K / s\ ]$

- delay s-blocks $\left[\ G(s) = \left(\frac{1 - k\ (\Delta t/2\ )\ s}{1 + k\ (\Delta t/2\ )\ s} \right)^{n}\ \right]$

b) and the user must provide the dc initial conditions for any other blocks if needed (see Point 1.).

Point 4.

When TACS does not calculate its own dc steady-state output values, it will nevertheless recognize any user-defined initial condition that can be used as of Point 1., in which case the user assumes all responsability for the whole dc initialization.

In such a case, the user must also remember to define any nonzero initial values of the "named entries" (columns 69-80) to the supplemental devices, unless these entries are other than previously-defined supplemental variables or devices, or than a signal source. (See Section 8.3.2)

Point 5.

Whether TACS does or does not calculate its own dc steady-state solution, the program will always take care of initializing the dc and ac history terms of the transfer functions and the transport delays. Remember that, in either case, the output values of all integrators and all delay s-blocks (see Point 3.) must be supplied by the user. There is no alternative.

Point 6.

When TACS calculates an ac steady-state solution at the basic frequency (the frequency of the first-read type-2 TACS source), then

a) TACS takes care of computing the output values of all order-zero blocks and all s-blocks without exception;

b) the ac contribution of all other blocks are totally ignored (the ac component of their output is assumed to be zero), except for the type-2 and type-90 signal sources defined as active in steady-state at the basic frequency (T-START < 0) .

Two golden rules

1) Make sure that all nonzero inputs to and output of the s-blocks and devices type 53, 58, 59, 62, 64 and 65 are defined for time t = 0.0 (either by the user or by the program).

2) For program-calculated steady-state solutions, make sure that integrator outputs, delay s-block outputs and named limits are all defined for time t = 0 .

8.4 1 Initialization of the Interfaced Variables

The steady-state initialization of the electrical network in the EMTP is calculated before the TACS steady-state initialization.

Consequence 1.

In the electrical network, the user must himself initialize any TACS variable (which are not yet calculated for time t = 0) by means of user-defined initial conditions in the EMTP or other sort of stratagem.

Consequence 2.

In the TACS steady-state initialization, the interfaced signals of sources type 90, 91, 92, 93 are defined and accessible at time t = 0., since they have already been calculated by the EMTP.

Consequence 3.

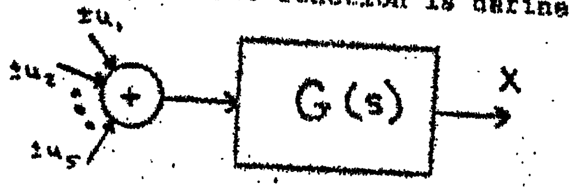
The respective EMTP and TACS steady-state initializations cannot be thought of as an interactive process, but as a sequential operation.

8.5 TACS Elements and Card Formats

8.5.1 Transfer Functions or $-blocks

This element is used to describe a transfer function of arbitrary order in "s". The operator "s" can be thought of as either the Laplace transform variable or as the "d/dt" operator.

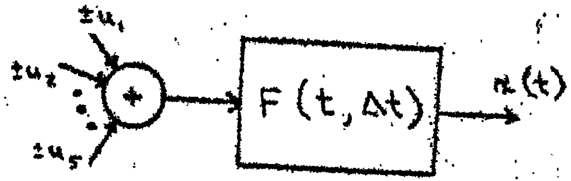
The n^{th}-order transfer function is defined as:



where

$$G(s) = GAIN \cdot \frac{N_0 + N_1 s + \dots + N_m s^m}{D_0 + D_1 s + \dots + D_m s^m}$$

and is solved as:



Examples of valid functions are:

$$\boxed{\frac{1}{1+Ts}} \quad \boxed{\frac{1}{s}} \quad \boxed{\frac{s}{1+Ts}} \quad \boxed{\frac{1+T_1 s}{1+T_2 s}}$$

$$\boxed{\frac{1+Ts}{s}} \quad \boxed{\frac{1+T_1 s}{(1+T_2 s)(1+T_3 s)}} \quad \boxed{\frac{1+T_1 s}{A+Bs+Cs^2}} \quad etc \dots$$

Format

N	OUTPUT NAME		±	IN₁		±	IN₂		±	IN₃		±	IN₄		±	IN₅		GAIN	FIXED -LO	FIXED -HI	NAMED -LO	NAMED -HI
I2	A6		A1	A6		A1	A6		A1	A6		A1	A6		A1	A6		E6.0	E6.0	E6.0	A6	A6

N₀	N₁	N₂	N₃	N₄	N₅	N₆	N₇
D₀	D₁	D₂	D₃	D₄	D₅	D₆	D₇
E10.0	E10.0	E10.0	E10.0	E10.0	E10.0	E10.0	E10.0

Rules

1. "N" is the order of the highest power of "s" of either numerator or denominator polynomials. Its value must be punched (right-justified) in columns 1-2 .

2. This block is identified by the alphanumeric name of its output. (Columns 3-8)

3. The total input to the block is the sum of any or all signed input signals. The sign character (+ or -) must be punched for all such non-blank inputs.

4. The value of a non-unity gain may be defined in columns 51-56 . When this field is left blank (or zero), GAIN = 1.0 is the default value automatically assigned by the program.

5. This block may also be defined as a dynamic limiter. See Section 8.5.3 for details.

6 The coefficients of the numerator (N_0, N_1, etc.) must be supplied on the next card(s). The order of the coefficients is identified by the fields they occupy on the card. For example, N_4, if nonzero, must appear in columns 41-50 and nowhere else.

7. The coefficients of the denominator (D_0, D_1, etc.) then follow on the next card(s). Here again, the order of the coefficients is identified by the field they occupy on the card. For example, D_1, if nonzero, must appear in columns 11-20 .

Examples

```
T1     +IN1       -IN2
     1.
     1.       0.1
TGR    +DERIV
     1.
              1.
CND    +ERR              -REF     +UNITY                0.25
     1.      0.14
     1.      0.04        0.04
```

) $OUT1 = \frac{1}{1+0.1s} \cdot (IN1 - IN2)$

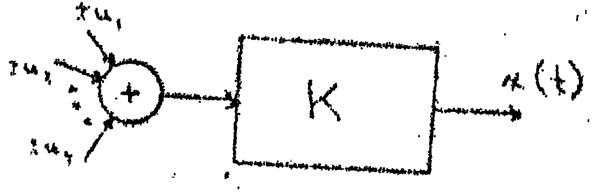
) $INTGR = 1/s \cdot DERIV$

) $SECND = 0.25 \cdot \frac{1+0.14s}{1+0.04s+0.04s^2} \cdot (ERR - REF + UNITY)$

8.5.2 Order-Zero Blocks (Z-Blocks)

This element is used to describe a linear relation between the output of the block and the sum of its inputs. It is used to specify simple summators, and potentiometers or amplifier settings. The name "order-zero" applies to this block when it is seen as the degenerate case of a transfer function which would have no term in "s".

This block is defined as:



where K is the gain setting.

Format

	OUTPUT		IN1		IN2		IN3		IN4		IN5		GAIN	FIXED LO	FIXED HI	NAMED LO	NAMED HI
[illegible]	A6	A1	A6	A1	A6	A1	A6	A1	A6	A1	A6		F6.0	F6.0	F6.0	A6	A6

Rules

1. The value of "N" may be punched as $\boxed{99}$ in columns 1-2, or else may be left blank or zero (since the order N is zero).
2. This block is identified by the alphanumeric name of its output, Columns 3-8.
3. Same as in 8.5.1
4. Same as in 8.5.1
5. This block may also be defined as a static limiter. See Section 8.5.3 for details.

Examples

```
99SUM2    +A     -ERR    +RERB
99EX3     +IN1   -LIM2                            0.072
99NEGMX   +SUM2  +EX3                            -0.82
```

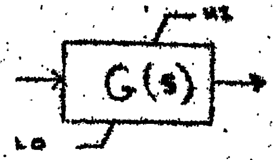
a) SUM2 = A - ERR + RERB

b) EX3 = 0.072 (IN1 - LIM2)

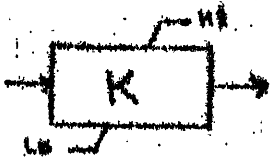
c) NEGMX = -0.82 (SUM2 + EX3)

8.5.3 Limiters

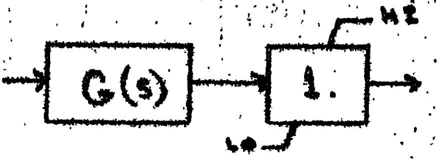
Low and/or high limits of fixed or calculated value can be superimposed on any transfer function block or order-zero block.



Dynamic limiter



Static limiter



Static limiter on a transfer function

Static limiter

The output value of an order-zero block is always calculated without considering any existing limit, and then, if the output value is seen to have exceeded either the lower or the higher limit values, the output value is readjusted according to the value of this limit or saturation level.

Dynamic limiter

The output value of an s-block is calculated differently depending on whether the element is operating inside or outside its defined limits. In the latter case, the derivatives of the output are automatically set to zero. Most limiters must be assumed to be of the static type, unless the user can positively identify that, for example, the complex impedance feedback loop of an amplifier is electrically modified or by-passed when the limit is reached.

ules

- Limits are defined on the card describing the element on which they apply. See Sections 8.5.1 and 8.5.2 .

- The user may define any combination of two types of limits: fixed and variable. (See table below) The fixed limits are defined as the "FIXED-LO" parameter and the "FIXED-HI" parameter of columns 57-62 and 63-68 respectively on the block card. The variable limits are defined by using the alphanumeric A6 names of other blocks or elements of the system, whose output will be the required calculated limit. These "NAMED-LO" and "NAMED-HI" identifications are punched respectively in the fields 69-74 and 75-80 of the block card.

3. The following table can be used to determine how the program interprets the different user-supplied combinations of fixed and variable limit definitions.

	A combination of:				is taken as:		
	FIXED -LO	FIXED -HI	NAMED -LO	NAMED -HI	LOW limit	HIGH limit	
NO LIMIT	---	---	---	---	-∞	+∞	
	0.	0.	---	---			
SINGLE LIMIT	A	---	---	---	A	0.	
	---	B	---	---	0.	B	
	---	---	LLL	---	LLL(t)	+∞	
	---	---	---	HHH	-∞	HHH(t)	
	1.	---	LLL	---	LLL(t)	0.	
	---	1.	---	HHH	0.	HHH(t)	
DOUBLE LIMIT	A	B	---	---	A	B	
	---	---	LLL	HHH	LLL(t)	HHH(t)	
	A	---	---	HHH	A	HHH(t)	
	---	B	LLL	---	LLL(t)	B	
DEGENERATE	B	A	---	---	A	A	for B > A
	B	---	---	---	0.	0.	for B > 0
	---	A	---	---	A	A	for A < 0
	A	---	---	HHH	HHH(t_1)	HHH(t_1)	for HHH(t_1) < A
	---	B	LLL	---	B	B	for LLL(t_1) > B

Notes

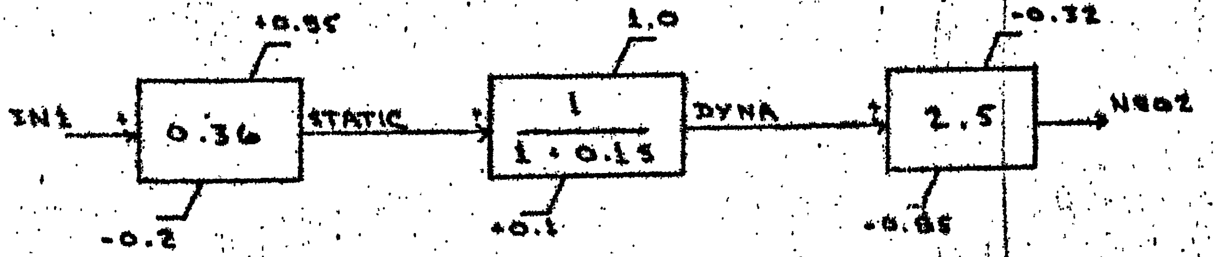
a) Check the above interpretations for each application.

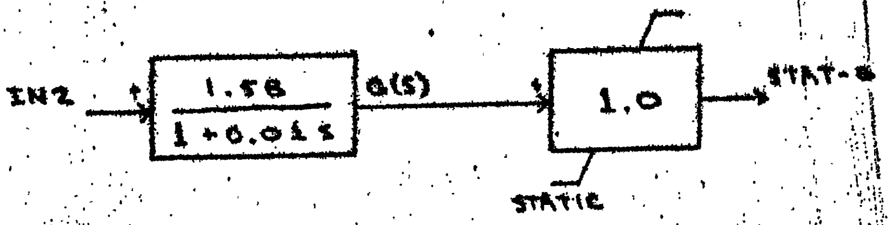
b) A warning message will be printed at the first occurrence of a criss-crossing of a double variable limit.

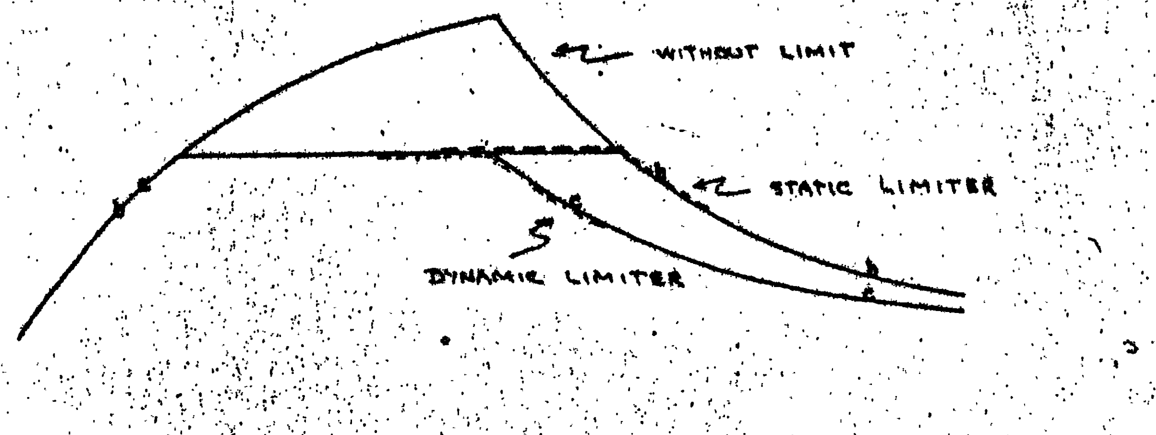
4. For operation of the limiters during steady-state dc and ac initialization, read the interpretation of messages 44 and 52 on pages 48e and 48h .

Examples

```
G    +G(S)                                               STATIC
     +IN2
.58
 1.       0.01
     +DYNA                              2.5  -0.85 -0.32
     +STATIC                                   0.1   1.0
 1.
 1.        0.1
G    +IN1                              0.36  -0.2  0.95
```







8.5.4 Signal Sources

TACS signal sources are signal generators that can be used as inputs to other blocks and elements of the system. Each source is defined on a single card as a separate system component. The user specifies the type and the name of the source according to the rules that are defined below.

Resident sources

Some source names are permanently available to the user as built-in TACS sources. They have pre-defined, reserved names, and need not be specified on a source card by the user. To use them as input to any other block or element, simply mention the name of the source as for any other input to a component. The resident sources are also available as voltage or current sources in the electrical network through the TACS-EMTP interface.

'TIMEX ' = simulation time in seconds (= 0.0 in steady-state)
'ISTEP ' = number of the present time step in the simulation
'DELTAT' = size of the time step (TIMEX = ISTEP * DELTAT)
'FREQHZ' = system frequency in Hz (as read from the 1st sinusoidal source)
'OMEGA ' = 2π* FREQHZ (in radians)
'ZERO ' = 0.0
'MINUS1' = -1.0
'PLUS1 ' = +1.0
'UNITY ' = 1.0 (kept for convenience only; use PLUS1)
'INFNTY' = +∞ (very large number fitting your computer system)
'PI ' = π

Format

TYPE	OUTPUT NAME		A	B	C		T-START	T-STOP
	A6		E10.0	E10.0	E10.0		E10.0	E10.0

Rules

1. The source is identified by the alphanumeric name of its output. (Columns 3-8)
2. T-START: = blank or 0.: source is activated at t>0
   = some value : source is activated at t≥value
   = negative : source is activated at t≤0 (except type 3, 4 and 91 for which a user-defined initial condition must be specified -- see Section 8.5.7)
3. T-STOP : = blank or 0.: source is never de-activated
   = value : source is de-activated at t≥value

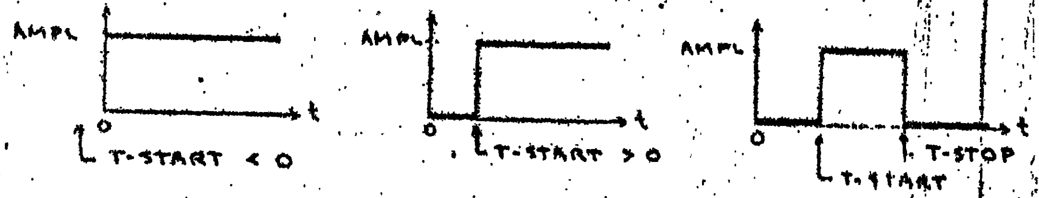
Note: When de-activated, the source signal is zero.

(continued next page).

4 Types of Sources

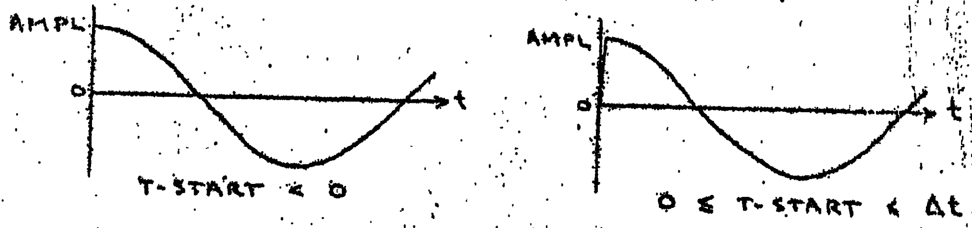
TYPE	A	B	C
01	AMPL	—	—
02	AMPL	FREQ (Hz)	φ (deg.)
03	AMPL	T (sec)	WIDTH (sec)
04	AMPL	T (sec)	—
90 91 92 93	—	—	—

TYPE = 01 : level signal

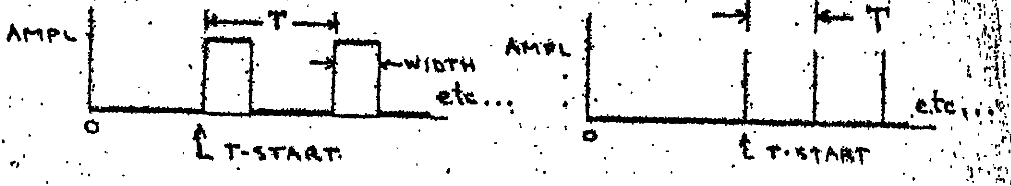


TYPE = 02 : output = AMPL * COS ($\omega t + \psi$)

= AMPL * COS ($2\pi f t + 2\pi\phi/360$)

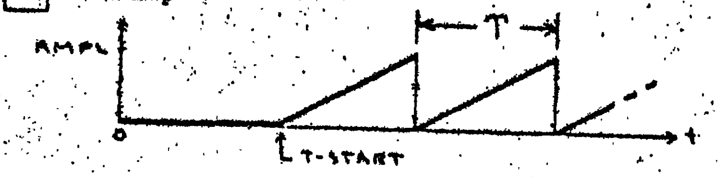


TYPE = 03 : pulse



(T-START ≤ 0 is valid, although this source cannot be included as active during the dc steady-state initialization unless a nonzero user-defined initial condition is specified as per Section 8.5.7)

TYPE = 04 : ramp



(T-START < 0 is valid, although this source cannot be included as active during the dc steady-state initialization unless a nonzero user-defined initial condition is specified as per Section 8.5.7)

TYPE = $\boxed{90}$ Output = EMTP node voltage

In which case the NAME must be a node name already defined in the electrical network. The output value is not calculated by TACS itself, but is simply made equal to the value of the voltage (with respect to TERRA), as measured at the node which bears the same name in the electrical network.

TYPE = $\boxed{91}$ Output = EMTP switch current

In which case the NAME must be a node name to which a switch (of any type) is connected in the electrical network. The output value of the source will then be set equal to the current flowing from the LEFT-node to the RIGHT-node, as defined on the EMTP switch card. In cases where more than one switch are attached to the said node, reference is assumed to be to the first of these switches, in the order of the data cards.

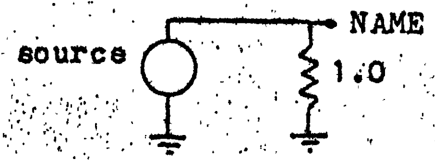
TYPE = $\boxed{92}$ Output = internal variable of special EMTP components

This source type is reserved for passing to TACS the values of certain internal variables of special EMTP components. For example, Rule 3 of Class 6 S.M. data cards (see Section 1.62) shows how rotor angles and angular velocities can be passed to TACS. This is for a dynamic synchronous machine (S.M.) source component, as used in subsynchronous resonance (SSR) studies. Such variables are then accessed (picked up and used) within TACS by means of the Type-92 TACS source component.

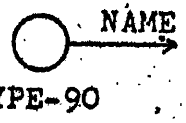
TYPE = $\boxed{93}$ Output = EMTP switch status $\begin{cases} =0 : \text{switch is open} \\ =1 : \text{switch is closed} \end{cases}$

The name of this TACS source must be a node name to which a switch (of any type) is connected in the electrical network. In cases where more than one switch are attached to the said node, reference is assumed to be to the first of these switches, in the order of the data cards.

Note: Any of the sources that can be defined in the electrical network (type 1 to 15) can also be used in TACS. Their value is passed to TACS as follows:



in the electrical network



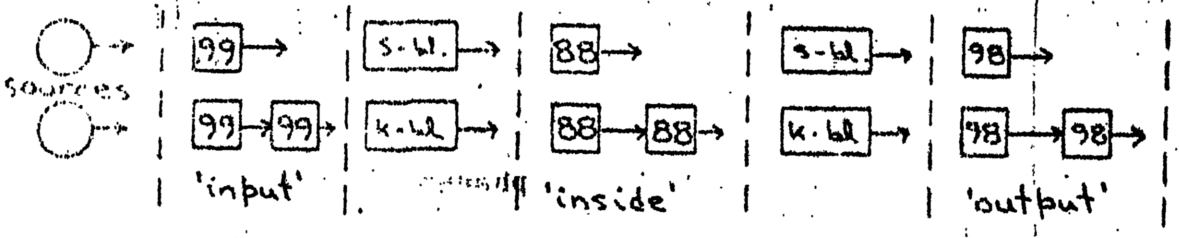
in TACS

8.5.5 Supplemental variables and devices

These elements are called "supplemental" because they differ from the linear s-blocks and z-blocks in the following way:

- they are not part of the solution matrix of the set of linear equations in TACS
- they are calculated sequentially, instead of simultaneously for the other s- and z-blocks (so that the data cards must be ordered accordingly) .

Supplemental variables may be part of three different groups of elements, as follows:



To make the solution simultaneous for the largest possible number of s-blocks and zero-order blocks, the user should keep the number of 'inside' supplemental elements as low as possible, and rather place the supplemental elements into the 'input' or the 'output' group, if applicable. (See Section 8.3.2)

The "input" group: type $\boxed{99}$

All the inputs to these "input" supplemental elements must be either TACS signal sources or the output of other supplemental "input" elements.

The "output" group: type $\boxed{98}$

The output of these supplemental "output" elements must not be used as input to any other block except other supplemental "output" elements. (Although they may be used as interfaced variables to the EMTP.)

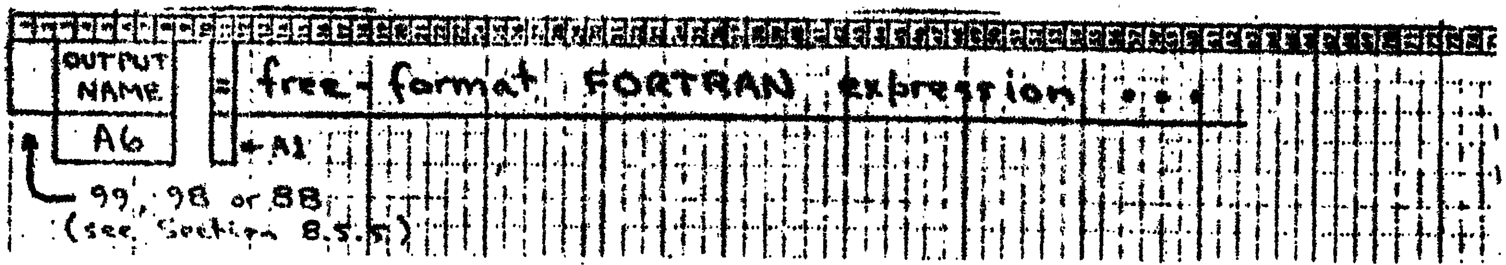
The "inside" group: type $\boxed{88}$

These are the leftover from the two previous groups. They must be used when, for example, the inputs and output are connected to elements of the system other than those allowed for the two previous groups. (See Section 8.3.2 for details of the calculation.)

A) The Algebraic and Logical FORTRAN Expression

Note: The older-type fixed-format variable has now been replaced by the free-format arbitrary FORTRAN expression described in this section. However, although the older type is not documented in this User's Manual anymore, it can still be accepted by the program for the convenience of those users wishing to continue running older versions of their data cases.

FORMAT :



RULES :

1. This variable is identified by the alphanumeric name of its output. (Columns 3-8)

2. The FORTRAN expression can be continued on as many cards as necessary Columns 1 - 80 are available on such continuation cards. Use the continuation character '$' to indicate that the next card is a continuation of the present card. To change the continuation character, see 'CHCONT' in Section 1.0g6 . The default character for the FORTRAN expression is '$' .

3 The character '=' must appear in column 11 of the first card of the expression.

4. All the rules for constructing standard FORTRAN expressions apply.

algebraic operators : + , - , * , / , **

logical operators : .OR. , .AND. , .NOT.

relational operators : .EQ. , .NE. , .LT. , .LE. , .GE. , .GT.

FORTRAN functions : SIN , COS , TAN , COTAN } with argument
SINH , COSH , TANH } in radians

ASIN , ACOS , ATAN (answer in radians)

EXP , LOG , LOG10 , SQRT , ABS

special functions :

TRUNC	(the integer part of ...)
MINUS	(sign inversion)
INVRS	(1.0 / arg)
RAD	(conversion from degrees to radians)
DEG	(conversion from radians to degrees)
SIGN	(= -1 if arg < 0 , = +1 if arg ≥ 0)
NOT	(= 0 if arg > 0 , = +1 if arg ≤ 0)
SEQ6	(= INT(modulo-6(arg)) (see below)

nesting : 20 levels

arguments : any of the TACS alphanumeric names of user-defined and resident variables
any numerical argument (either integer or real)

5. All functions accept only one argument, as in SQRT(arg) . Valid arguments are either a TACS name, a numerical constant, or another function, as in SQRT(ABS(INVRS(X))) .

6 The characters '+', '-', '*', '/', ')', '(' and blank are separator characters, and cannot be part of a TACS alphanumeric that is going to be used in a FORTRAN expression.

```
ex.: 'VAR1  ' and ' VAR1' will both be interpreted as 'VAR1  '
     'VAR-1 ' will be interpreted as 'VAR   ' - 1.0
     'VAR A ' will be interpreted as 'VAR   ' followed
              by 'A     ' (here meaningless)
     '1.0 E6' will be interpreted as 1.0 followed
              by 'E6    ' (here meaningless)
```

Note: Dots ('.') may be embedded within a name.

7 Any TACS alphanumeric variable can be associated with either algebraic or logical operators, regardless of whether it is itself of algebraic or logical contents (no such distinction in TACS) .

Thus, if a logical expression is used in an algebraic context, its value will be considered as either =0.0 or =1.0 (for respectively '0' and '1').

Similarly, if an algebraic expression is used in a logical context, its value will be considered as either '0' or '1' (for respectively ≤0.0 and >0.0). .

EXAMPLES :

```
9ANGLE   =DEG( ATAN(CNTRL - BIAS2))  + 36.2
8EXPR    =-A * ( B+ C**(-D +3))   $
 4. E / PI
9FIFTY   =   50.
8IF3          .NOT. A+B  .LT. 3  .AND. (ISTEP .GE. 100  $
     .OR. .NOT. FLAG2 )
```

About SEQ6 :

arg :	-1	0	1	2	3	4	5	6	7	8	etc.
SEQ6(arg):	5	6	1	2	3	4	5	6	1	2	

(the output is an integer)

B) The "Devices"

Format:

Type	OUTPUT NAME	Code	±	IN_1	±	IN_2	±	IN_3	±	IN_4	±	IN_5	A	B	C	D	E
I2	A6	I2	A1	A6	A1	A6	A1	A6	A1	A6	A1	A6	E6.0	E6.0	E6.0	A6	A6

Rules:

0. TYPE = $\boxed{99}$, $\boxed{98}$ or $\boxed{88}$. See 8.5.3 above.

1. This device is identified by the alphanumeric name of its output. (Columns 3-8)

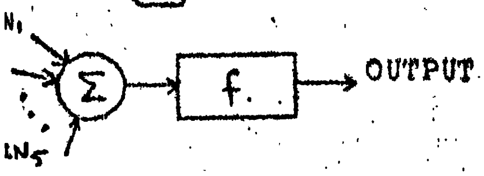
2. The total input to the device is the sum of any or all signed input signals (except for devices type 60 , 61 and 63 where each input signal is interpreted individually) . The sign character (+ or -) must be punched for all non-blank inputs.

3. The different devices are:

CODE

50 : frequency-sensor
51 : relay-operated switch
52 : level-triggered switch
53 : transport delay
54 : pulse transport delay
55 : digitizer
56 : point-by-point user-defined non-linearity
57 : multi-operation time-sequenced switch
58 : controlled integrator
59 : simple derivative
60 : input-IF component
61 : signal selector
62 : sample and track
63 : instantaneous min/max
64 : min/max tracking
65 : accumulator and counter

ODE = 50 : Frequency meter

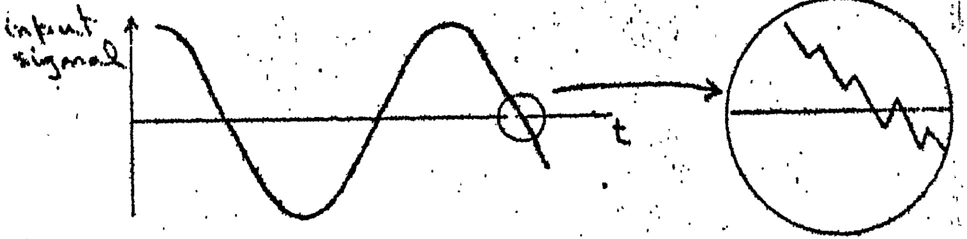


A : initial frequency (Hz)

B C D E : ignored

OUTPUT = measured frequency of the input

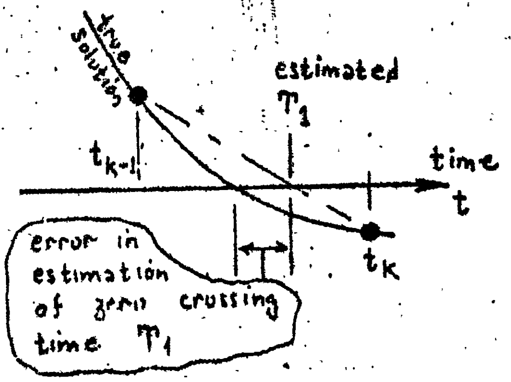
The time between successive zero-crossings of the input signal is measured and converted to a frequency value in Hertz. The device will automatically reject higher-frequency non-characteristic oscillations appearing on the main signal. Alternately, the user may choose to process the input signal through a low-pass filter [1 / (1 + T·s)], in cases where the input noise causes difficulties in measuring the main signal frequency.



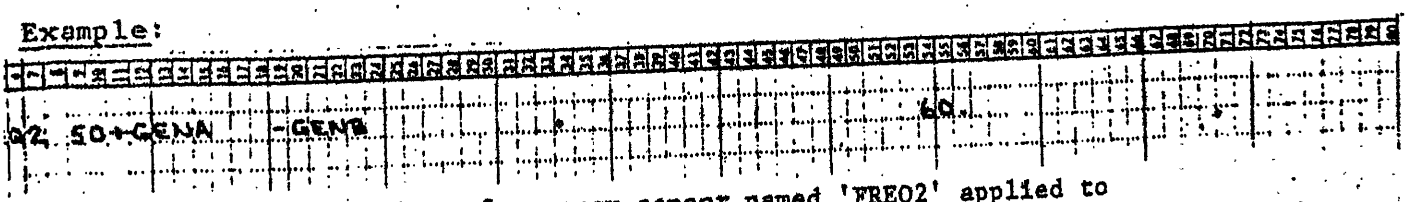
As for the algorithm used, let T_1 be the time of the most-recent zero crossing, and T_2 the time of the one preceding that. Then the current frequency estimate f is given by:

$$f = \frac{0.5}{T_1 - T_2}$$

Of course one rarely knows the times of zero crossing exactly; linear interpolation (see sketch) is used to estimate these.



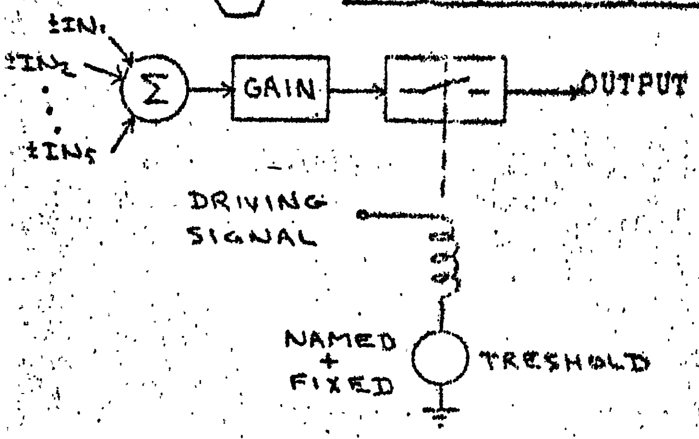
Example:



Q2 50+GENA -GENB 60.

This card would describe a frequency-sensor named 'FREQ2' applied to the sum of the inputs ['GENA' - 'GENB'] . Initial frequency of 60 Hz .
Note: this value of 60 Hz will not change until at least two zero-crossings of the signal have been detect d, so that an interval can be measured.

CODE = ⟨51⟩ : Relay-operated switch



[A] : value of the GAIN (def.=1.0)
[B] : value of FIXED TRESHOLD
[C] : { 0 : normally-open
          1 : normally-closed
[D] : NAMED TRESHOLD (optional)
[E] : DRIVING SIGNAL

{ if switch is closed, OUTPUT = GAIN * sum(inputs)
{ if switch is open , OUTPUT = 0.0

The switch will operate from its "normal" state when:

{ if normally-open, when |DRIVING SIGNAL| ≥ NAMED + FIXED TRESHOLDS
{ if normally-closed, when " " < " " "

Note: [D] and [E] can be the names of any other TACS variable (See examples below.)

CODE = ⟨52⟩ : Level-triggered switch

This device is defined in exactly the same way as the relay. The only difference in the operation of the level-trigger, as opposed to the relay, is that the actual value of the driving signal is taken (instead of the absolute value), and is compared to a treshold which here can be either positive or negative.

Examples:

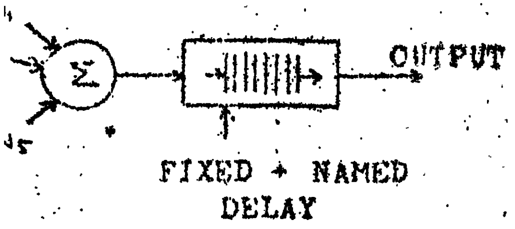
```
REL-A 51+UNITY                                              0.5           SIG2
REL-B 51          +IN1     -BIAS                       2.0          1.TRESH DRIV1
DETECT52          +SOURCE                                  1.36        TR-2 ANY
```

a) 'REL-A' = 'UNITY' when |'SIG2'| ≥ 0.5

b) 'REL-B' = 2·('IN1' − 'BIAS') when |'DRIV1'| < 'TRESH'

c) 'DETECT' = 'SOURCE' when 'ANY' ≥ 'TR-2' + 1.36

CODE = ⟨53⟩ : Transport delay



[B] : value of FIXED DELAY (sec)
[C] : value of MAX. DELAY (sec)
[D] : NAMED DELAY (optional)
[A] [E] ignored

At any time "t", for a value of total delay = T sec. ,

OUTPUT(t) = INPUT(t-T)

Note about the variable 'NAMED DELAY':

When the user wants the value of the delay to be variable (as opposed to 'fixed'), he may define this delay as being the output of some other TACS block at which the delay itself is calculated.
In such a case, the user must also specify the maximum value that will be reached by the total delay time, and punch this maximum value in field 'C' of the device card.
(The program needs to know ahead of time how many cells of memory are to be allocated to the storage of the 'past history' of the input signal.)

Examples:

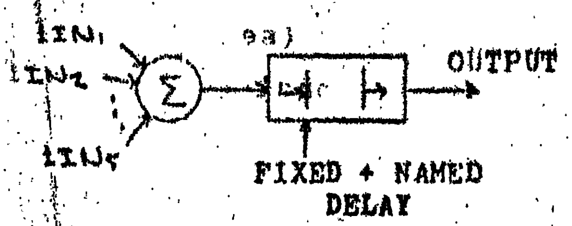
```
DEL-A 53+SIGNAL  ...   0.002   .004SLOW2
DEL-B 53+IN2           .0035
```

'DEL-A'(t) = 'SIGNAL'(t-T) where T = 'SLOW2' + 0.002 { T_{max}=0.004 }

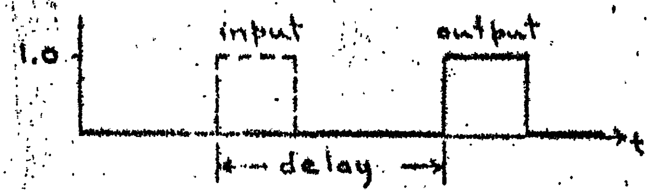
'DEL-B'(t) = 'IN2'(t - 0.0035)

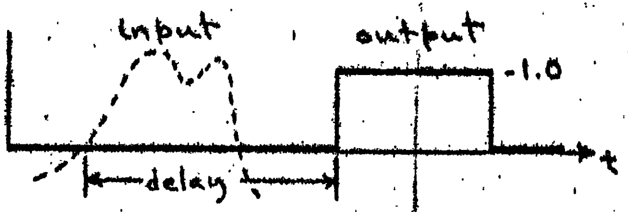
Note: When the input signal is known to be a pulse or a succession of pulses, the user should consider using a 'pulse transport delay' instead of this 'storage-hungry' device.

CODE = (54) : <u>Pulse delay</u>



A	: value of i.c. T-ON (see below)
B	: value of FIXED DELAY (sec)
C	: value of i.c. T-OFF (see below)
D	: NAMED DELAY (optional)
E	ignored



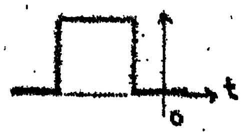


<u>Note</u>: Constraint on the frequency of the input signal.

Overall period of input > pulse width + delay .

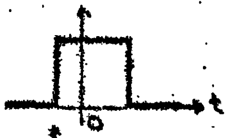
<u>Initial conditions T-ON and T-OFF</u>

The user can make the OUTPUT respond to an input signal which partly or totally occurred before simulation time t > 0 . This situation can be simulated as follows:

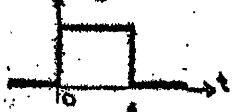


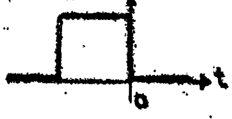
specify T-ON in field 'A' of the card
specify T-OFF in field 'C'

where T-ON < T-OFF < 0

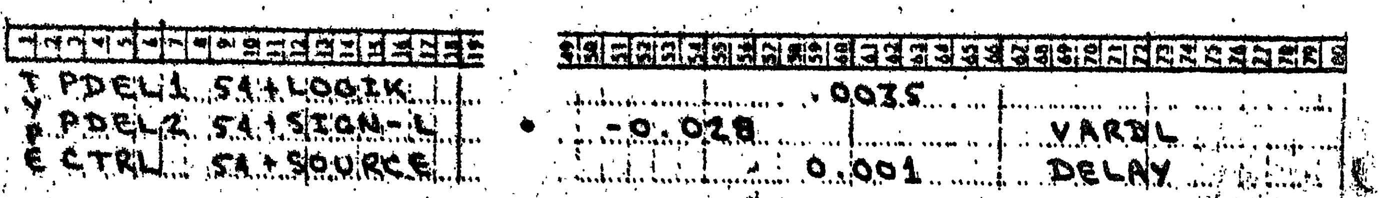


specify T-ON only in field 'A'
<u>note</u>: There is no need to specify T-OFF here, since it will be detected by the program itself.





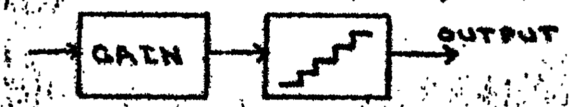
When reading the cards, the computer does not make the difference between a blank field and the value 0.0 . If the user does want to specify a value of T-ON or T-OFF that is exactly 0.0, he must instead specify a value that is negative and very close to 0.0 (< Δt), but is not exactly 0.0 .

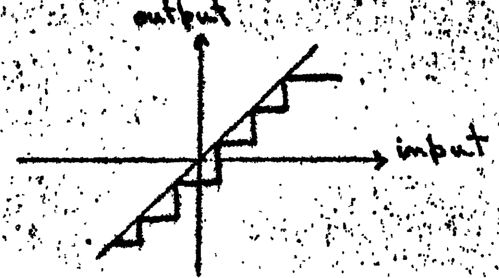


```
T PDEL1 54+LOGIK              .0035
Y PDEL2 54+SIGN-L    -0.028                     VARDL
E CTRL  54+SOURCE              0.001            DELAY
```

'PDEL1'(t) = 'LOGIK'(t-0.0035)
'PDEL2'(t) = 'SIGN-L'(t-'VARDL') , with the input being 'ON' since 0,028 seconds prior to the beginning of the simulation.
'CTRL'(t) = 'SOURCE'(t-T) where T = 'DELAY' + 0.001

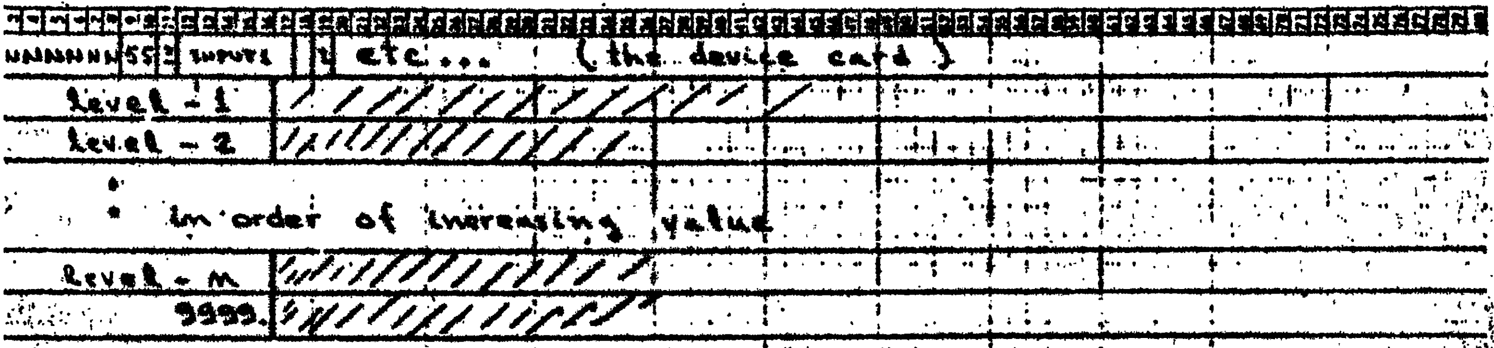
CODE = ⟨55⟩ : Digitizer





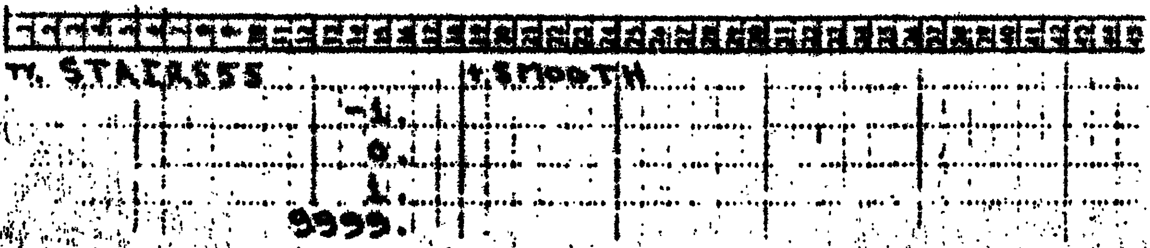
Sp cify the GAIN in field 'A' of the card (defaulted to 1.0)

Specify the levels (enough to cover the expected range) by punching as many cards as there are levels, one value of level per card. End with a 'terminator' card : punch '9999' in columns 13-16 .

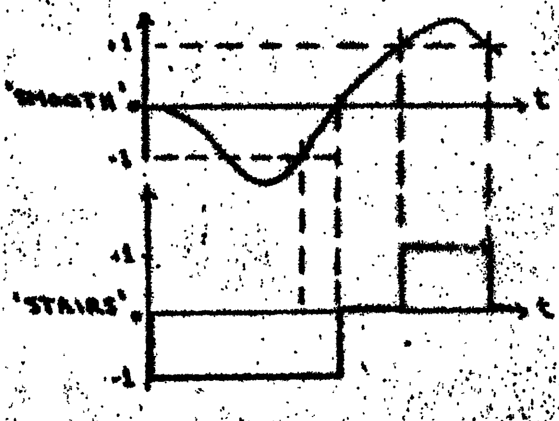


```
NNNNNN55 INPUTS   etc...  (the device card)
     Level - 1
     Level - 2
 .
 .   in order of increasing value
     Level - m
         9999.
```

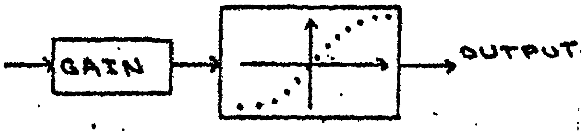
Example:



```
TT. STAIRS55      +SMOOTH
              -1.
               0.
               1.
           9999.
```



CODE = ⟨56⟩ : Point-by-point non-linearity



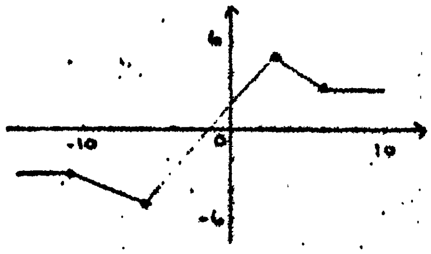
Specify the GAIN in field 'A' of the card (defaulted to 1.0) .

Define the function y = f(x) with as many points as needed to cover the expected range of variation (linear interpolation is performed by the program for values between the given points) .
Specify one such point per card by punching the pair of coordinates (x,y) .
Place the cards in order of increasing values of 'x' .
End with a 'terminator' card : punch '9999' in columns 13-16 .

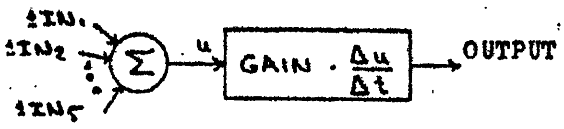
NNNNNN 57. INPUT1	etc ... (the device card)	
x_1	y_1	
x_2	y_2	
⋮	⋮ in order of increasing value of 'x'	
x_m	y_m	
9999.		

Example:

TY. NL	56+X	
	-1000.	-3.
	-11.	-3.
	-6.	-5.
	3.	5.
	6.	3.
	1000.	3.
	9999.	



CODE = ⟨59⟩ : Simple derivative



A : value of the GAIN (defaulted to 1.0)

B C D E : ignored

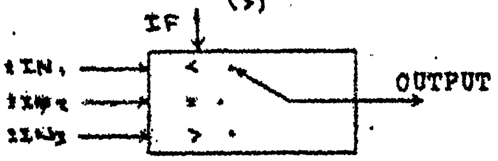
$$\text{OUTPUT}(t) = \text{GAIN} \cdot \frac{u(t) - u(t - \Delta t)}{\Delta t}$$

Note: This device will be properly initialized by the program at $t = 0.0$, provided that all the initial conditions for the inputs IN_1, IN_2, etc. are available (either program-calculated or user-defined). See Section 8.4 .

To assign a nonzero initial value to the OUTPUT, specify also a user-defined initial condition as per Section 8.5.7 .

CODE = ⟨60⟩ : Input-IF component

$$\text{SIGNAL1} \left\{\begin{matrix}<\\=\\>\end{matrix}\right\} \text{SIGNAL2} + \text{CONSTANT} .$$



A : numerical CONSTANT (optional)

D : name of SIGNAL1

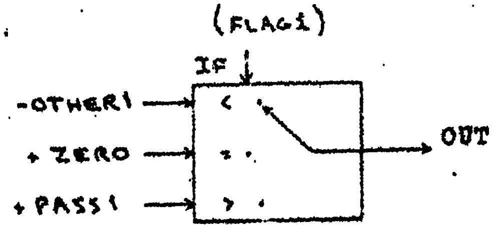
E : name of SIGNAL2 (optional)

B C : ignored

$$\text{if SIGNAL1} \left\{\begin{matrix}<\\=\\>\end{matrix}\right\} \text{SIGNAL2} + \text{CONSTANT} , \quad \text{OUTPUT} = \left\{\begin{matrix}\pm IN_1\\ \pm IN_2\\ \pm IN_3\end{matrix}\right\}$$

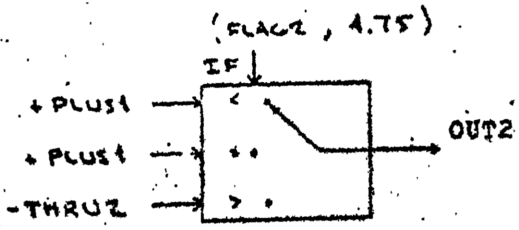
Note: For this device, the inputs are not summed up. Each input is interpreted individually.

Examples



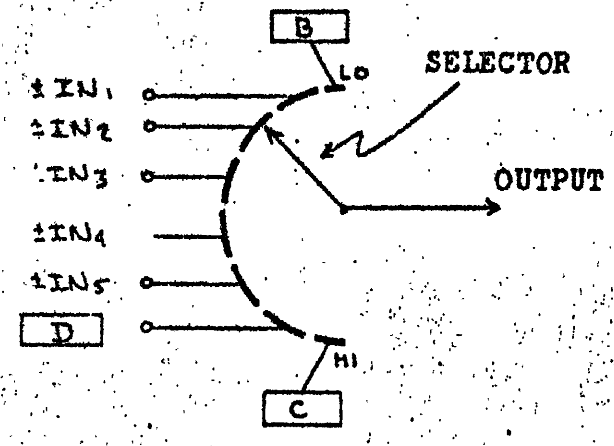
$$\text{if FLAG1} \left\{\begin{matrix}<\\=\\>\end{matrix}\right\} 0.0 , \quad \text{OUT} = \left\{\begin{matrix}\text{-OTHER1}\\ \text{ZERO}\\ \text{PASS1}\end{matrix}\right\}$$

note: FLAG1 can itself be a more complex logical/algebraic expression defined in a FORTRAN expression



$$\text{if FLAG2} \left\{\begin{matrix}<\\=\\>\end{matrix}\right\} 4.75 , \quad \text{OUT2} = \left\{\begin{matrix}\text{PLUS1}\\ \text{PLUS1}\\ \text{-THRU2}\end{matrix}\right\}$$

CODE = ⟨61⟩ : Signal selector



$\boxed{B}$: output LO when SELECTOR 0.5

$\boxed{C}$: output HI when SELECTOR 6.5

$\boxed{D}$: name of 6th input (or blank)

$\boxed{E}$: name of SELECTOR variable

$\boxed{A}$: ignored

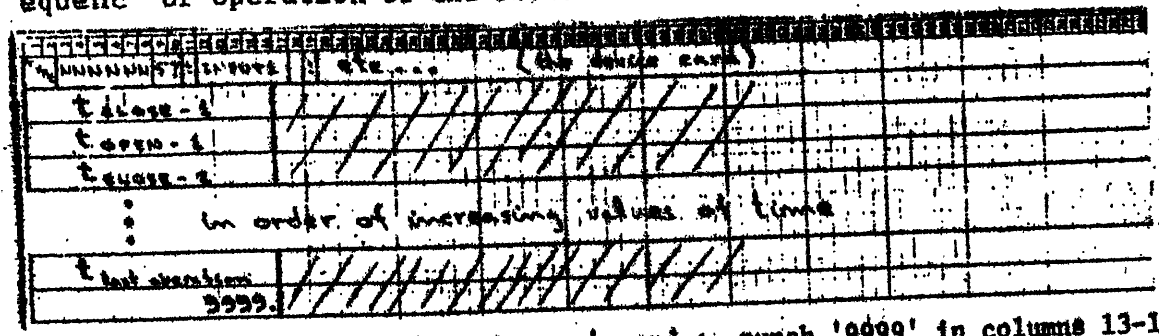
$$\text{if SELECTOR} \begin{Bmatrix} = 1.0 \pm 0.5 \\ = 2.0 \pm 0.5 \\ = 3.0 \pm 0.5 \\ = 4.0 \pm 0.5 \\ = 5.0 \pm 0.5 \\ = 6.0 \pm 0.5 \end{Bmatrix}, \quad \text{OUTPUT} = \begin{array}{ll} \boxed{\pm IN_1} & \text{(default = 0 0)} \\ \boxed{\pm IN_2} & \quad '' \qquad '' \\ \boxed{\pm IN_3} & \quad '' \qquad '' \\ \boxed{\pm IN_4} & \quad '' \qquad '' \\ \boxed{\pm IN_5} & \quad '' \qquad '' \\ \boxed{D} & \quad '' \qquad '' \end{array}$$

$$\text{if SELECTOR} \begin{bmatrix} < 0.5 \\ \geqslant 6.5 \end{bmatrix} \begin{array}{l} , \quad \text{OUTPUT} = \boxed{B} \\ , \quad \text{OUTPUT} = \boxed{C} \end{array}$$

Note: For this device, the inputs are not summed up.
Each input is interpreted individually.

CODE = ⟨57⟩ : Time-sequenced switch

This switch is assumed to be initially open. The user specifies the equenc of operation of the switch as follows:


NNNNNN57 INPUT etc... (the device card)
t close-1
t open-1
t close-2
in order of increasing values of time
t last operation
9999.

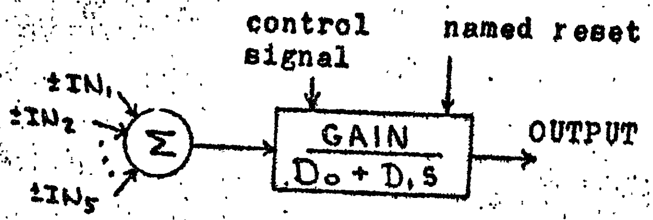
Remember to end with a 'terminator' card : punch '9999' in columns 13-16 .

Note: Since the devices are ignored during the program-calculated steady-state initialization, this switch is also open during steady-state. However, since user-defined initial conditions may be defined for any TACS variable, the user may choose to define a nonzero initial condition for the output of this device, thus bypassing the effect of this stubbornly-open switch at t = 0.

Example:

```
TY.SWCTRLST+UNITY
        0.0025
        0.0030
        0.0105
        0.0110
        0.0205
         9999.
```

CODE = (58) Controlled integrator

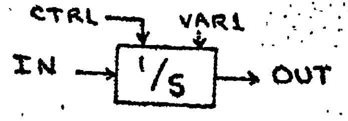


A	: value of GAIN (def. = 1.0)
B	: value of D_0 (possibly 0.0)
C	: value of D_1 (possibly 0.0)
D	: name of the control signal
E	: named reset value (or blank)

$$\left.\begin{array}{l}\text{if control signal} > 0.0 \\ \text{if no control signal name}\end{array}\right\} \longrightarrow : \text{OUTPUT} = \frac{\text{GAIN}}{D_0 + D_1 \cdot s} \cdot \text{sum(inputs)}$$

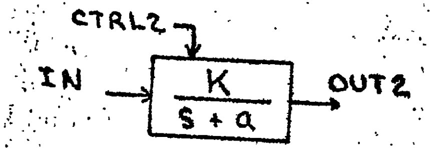
if control signal $\leq 0.0 \longrightarrow$: OUTPUT = value of named reset (or 0.0 if no name specifi d)

Applications



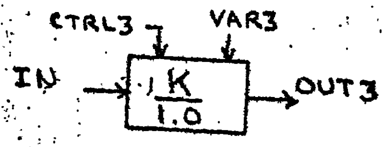
$$\left\{\begin{array}{l}\text{if CTRL} > 0, \quad \text{OUT}(t) = \text{OUT}(t - \Delta t) + \int_{t-\Delta t}^{t} \text{IN}(\eta)\, d\eta \\ \text{if CTRL} \leq 0, \quad \text{OUT}(t) = \text{VAR1}(t)\end{array}\right.$$

(which will also be used as initial condition for the next time step)



$$\left\{\begin{array}{l}\text{if CTRL2} > 0, \quad \text{OUT2} = \frac{K}{s + a} \cdot \text{IN} \\ \text{if CTRL2} \leq 0, \quad \text{OUT2} = 0.0\end{array}\right.$$

(same remark as abov)



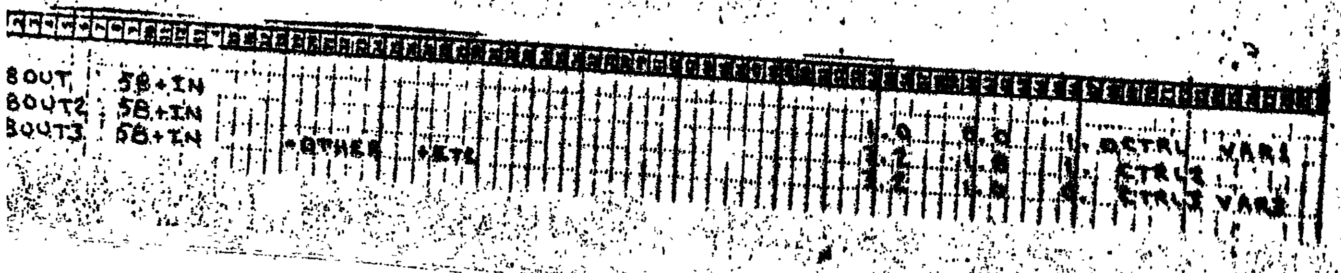
$$\left\{\begin{array}{l}\text{if CTRL3} > 0, \quad \text{OUT3} = K \cdot \text{IN} \\ \text{if CTRL3} \leq 0, \quad \text{OUT3} = \text{VAR3}\end{array}\right.$$

Note: In a previous version of this program, the type-58 device has also been used as a counter. This function is now served more flexibly by the device type 65 . However, for the convenience of users wishing to run older versions of their data cases, th "counter" function of this type-58 device is kept operational, and is defined as follows:

D : the keyword 'COUNTR'

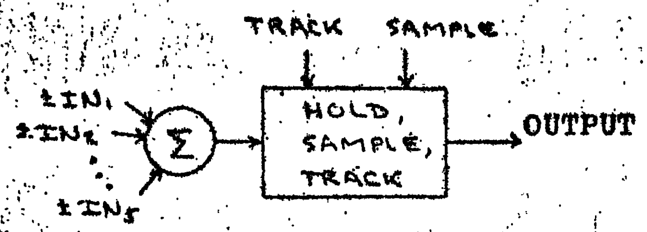
A B C E : ignored

and OUTPUT(t) = OUTPUT(t - Δt) + sum(inputs)



```
8OUT   58+IN                          1.0  0.0  1. CTRL   VAR1
8OUT2  58+IN                          1.2  1.0  1. CTRL2
8OUT3  58+IN   -OTHER  +ETC           1.2  1.0  0. CTRL3  VAR3
```

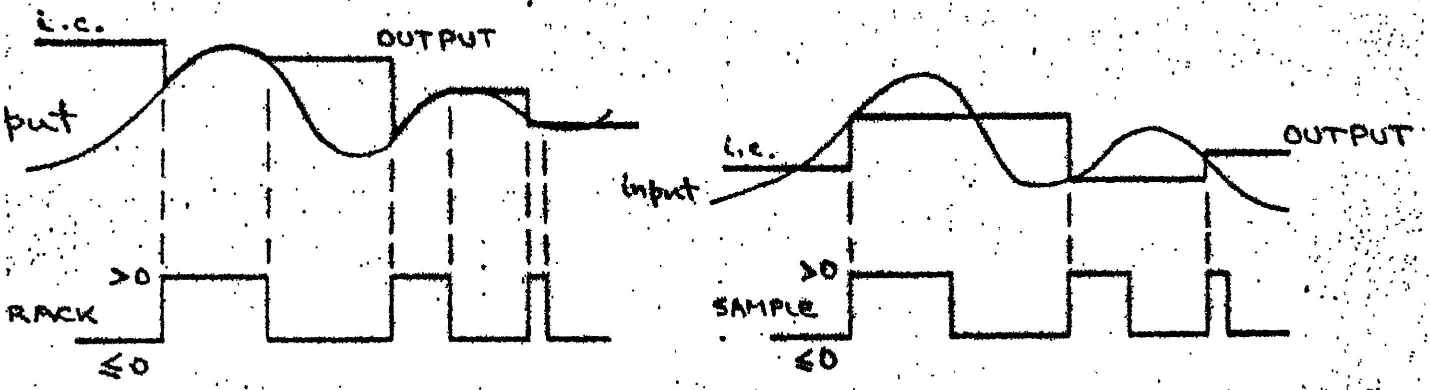
CODE = 62 : Sample and Track



D : name of TRACK signal (or blank)

E : name of SAMPLE signal (or blank)

A B C : ignored



Note: In the absence of both TRACK signal and SAMPLE signal, the OUTPUT is in HOLD mode.

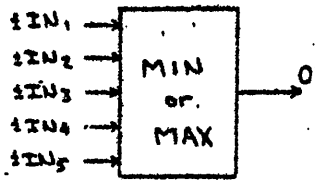
Note: The TRACK signal supercedes the SAMPLE signal, should both control signals be > 0 simultaneously.

Note: The SAMPLE mode involves a two-step operation. The order to sample a new value is only performed on the rising front of the SAMPLE control signal, which must then be reset to ≤ 0 before the next SAMPLE order is given.

Note: The TRACK operation becomes equivalent to a SAMPLE operation if the TRACK control signal lasts only one time step.

To assign a nonzero initial condition to the OUTPUT (the initial HOLD value), specify a user-defined initial condition as per Sect. 8.5.7 .

CODE = $\langle 63 \rangle$: Instantaneous minimum/maximum



$\boxed{B}$: = -1.0 to get minimum
= +1.0 to get maximum

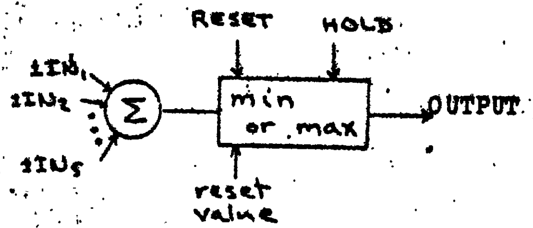
$\boxed{A}$ $\boxed{C}$ $\boxed{D}$ $\boxed{E}$: ignored

if $\boxed{B}$ = -1.0 , OUTPUT = min($\pm IN_1$, $\pm IN_2$,..., $\pm IN_5$)

if $\boxed{B}$ = +1.0 , OUTPUT = max(" " ")

Note: For this device, the inputs are not summed up. Each input is interpreted individually.

CODE = $\langle 64 \rangle$: Minimum/maximum tracking



$\boxed{B}$: = -1.0 to get minimum
= +1.0 to get maximum

$\boxed{C}$: numerical reset value

$\boxed{D}$: name of RESET signal (or blank)

$\boxed{E}$: name of HOLD signal (or blank)

$\boxed{A}$: ignored

if RESET signal > 0.0 , OUTPUT = $\boxed{C}$

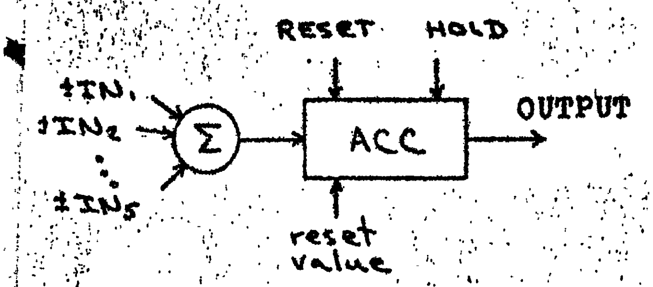
else if HOLD signal > 0.0 , OUTPUT(t) = OUTPUT(t - Δt)

else
if $\boxed{B}$ = -1.0 , OUTPUT(t) = min(OUTPUT(t- Δt), input(t))
if $\boxed{B}$ = +1.0 , OUTPUT(t) = max(OUTPUT(t- Δt), input(t))

Note: This device will be properly initialized by the program at t = 0.0 , provided that the initial condition for the OUTPUT value is supplied.

To assign a nonzero initial condition to the OUTPUT (which will also be the starting minimum or maximum) , specify a user-defined initial condition as per Section 8.5.7 .

CODE = ⟨65⟩ : Accumulator and counter



$\boxed{\text{C}}$: numerical reset value

$\boxed{\text{D}}$: name of RESET signal (or blank)

$\boxed{\text{E}}$: name of HOLD signal (or blank)

$\boxed{\text{A}}$ $\boxed{\text{B}}$: ignored

if RESET signal > 0.0 , OUTPUT = $\boxed{\text{C}}$

else if HOLD signal > 0.0 , $\text{OUTPUT}(t) = \text{OUTPUT}(t-\Delta t)$

else $\boxed{\text{OUTPUT}(t) = \text{OUTPUT}(t-\Delta t) + \text{input}(t)}$

Not : This device will be properly initialized by the program at $t = 0.0$, provided that the initial condition for the OUTPUT value is supplied.

To assign a nonzero initial condition to the OUTPUT (which will also be the initial accumulator contents) , specify a user-defined initial condition as per Section 8.5.7 .

Special application:

PLUS1 $\longrightarrow \boxed{\text{ACC}} \longrightarrow$ OUTPUT $\left\{ \begin{array}{l} \text{provides a straightforward} \\ \text{step counter} \\ \text{with and without reset} \end{array} \right.$

8.5.6 Printed/Plotted Output of the TACS Variables

The time-varying values of the signals and variables in TACS are calculated by the program at discrete intervals of time $t = 0, \Delta t, 2\Delta t$, etc...

Just as for the electrical network, the value of each variable in TACS can be observed in printed or plotted form. (See Sect. 1.8a) Under user control are:

a) which variables are to be printed or plotted (see specifications below)

b) the printing and plotting intervals IOUT and IPLOT (see Sections 1.0h and 1.1b)

c) the printout of the minima and maxima of the output variables (see Section 1.0h : MAXOUT)

d) permanent disk storage of the plot data points (see Section 1.0h : ICAT)

e) program diagnostic printout (see Section 1.0h : IPRSUP)

To specify which TACS variables are to be printed or plotted

a) for output of all the variables

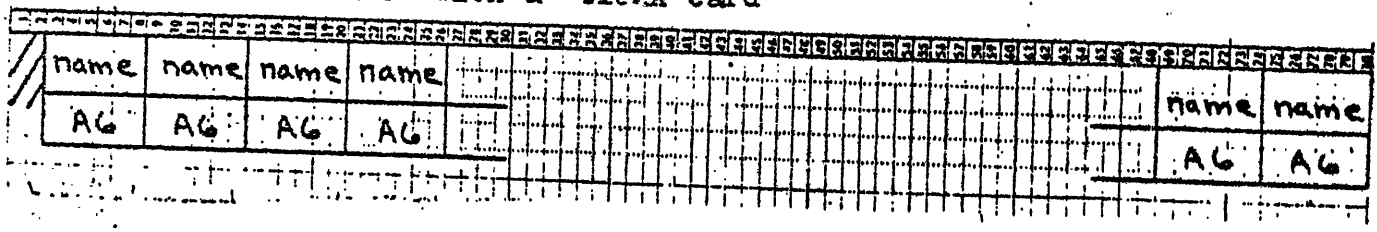
a single card is needed, with a '1' in column 2

or

b) for output of only some variables

use as many cards as needed, in the following format,

→ and terminate with a blank card



note; any of the A6 fields on any one output card may be blank, provided that at least one field per card is non-blank .

As for locating the TACS variables which have been so requested in the resultant printout, a pair of A6 names is used. The first is always "TACS", and the second is the user-supplied name of the TACS variable. For plotting purposes (either batch-mode or interactive), this same pair of names is used, and TACS variables are treated as if branch currents were involved (Type-9 plot variables). This presumes a hybrid problem with both TACS and also some electric network representation. For a TACS-only data case, TACS variables are treated like node voltages (Type-1 or 4 for plotting purposes), and only a single name (that of the TACS variable) is used for identification.

8.5.7 TACS User-Defined Initial Conditions

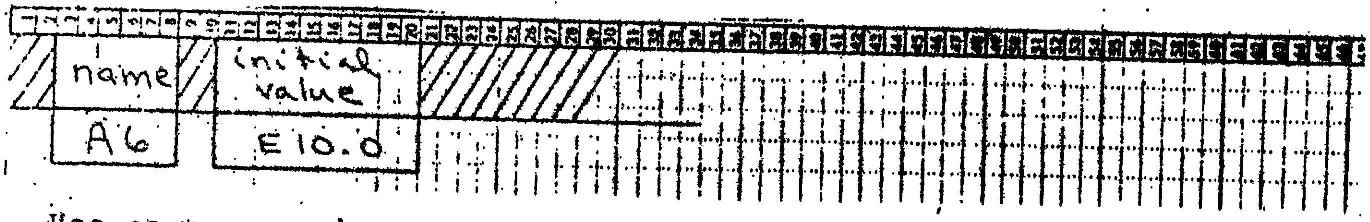
Steady-state initialization as calculated by the program is discussed in Section 8.4 .

The initial value at t = 0.0 of variables not covered by the program initialization calculations can be provided by the user, in the format presented below.

Typically, the following elements will require user-defined Initial conditions for t = 0.0 .
The default value of unspecified initial conditions is zero .

- integrators $\frac{1}{s}$
- delay s-blocks $\left(\frac{1 - k\,\Delta t/2 \cdot s}{1 + k\,\Delta t/2 \cdot s}\right)^n$
- FORTRAN expressions
- devices 50, 51, 52 etc...
- sources type 3 and 4 (pulse and ramp)
- sources where T-START is not specified or is 0.0 .

ormat



Use as many cards as required, and
→ terminate with a blank card (whether any init. cond. are defined or not)

This blank card also marks the end of the TACS data case altogether.

"
"
A
"
"
A
A
"
A
A

"
B
"
B

B
B
B
B
B

"
"
Ca

Ca
"
Ca
Ca
CD
"C
Cf
"C
"C
Co
Co

9. INDEX OF EMTP RULE BOOK

Topic of Interest to EMTP User . . . Page

"ABSOLUTE TACS DIMENSIONS" to size TACS tables (Sect. 1.0e5) . . . 4b-2
"ABSOLUTE U.M. DIMENSIONS" to size U.M. tables (Sect. 1.0e14) . . . 4c-3
Accumulator and counter, Type-65 TACS device (Sect. 8.5.5) . . . 311
Acknowledgement of contributing parties (Sect. 0.2) . . . iv-a
Active gap of surge arrester, Type-94 (Sect. 1.34) . . . 25a
AEP Service Corp. See "IBM".
'ALTERNATE DIAGNOSTIC PRINTOUT" definition (Sect. 1.0g8) . . . 4e-9
'AMETANI SETUP" request for transfer to it (Sect. 1.0g) . . . 4e
'AMETANI SETUP" supporting routine (Sect. 7.6) . . . 231
nalog computer simulation using TACS (Sect. 8.) . . . 274
'ANALYT" subroutine for user-supplied FORTRAN (Sect. 1.9c) . . . 39a
ANALYTIC SOURCES USAGE" signals use of "ANALYT" (Sect. 1.0g1) . . . 4e-1
node of valve/diode switch component (Sect. 1.43) . . . 30c
rmor of "CABLE CONSTANTS" (Sect. 7.7.1) . . . 251
ARRDAT" routine for ZnO exponential fitting (Sect. 7.2b) . . . 103h
rrester modeling. See "Surge arrester modeling".
vailability of program (Section 0.1) . . . iv

se voltage of statistical tabulation (Sect. 1.8b, BASEV) . . . 38c-1
sin Electric Power Cooperative. See "Honeywell".
BEGIN NEW DATA CASE" for data case separation (Sect. 1.0a) . . . 4
BEGIN PEAK VALUE SEARCH" for delayed extrema (Sect. 1.0e11) . . . 4c
essel functions of line constants. See "Skin effect".
BLANK " cards of data case (Sect. 1.-a) . . . 1a
nneville Power Administration (Section 0.2) . . . iv-a
. See "Bonneville Power Administration".
nch cards as EMTP data classification (Sect. 1.a-4) . . . 1
anch output variables (Sect. 1.8a, Branch outputs) . . . 38a
andwajn, Dr. Vladimir. See Sect. 1.62 mention. . . . 34d-1
ndling of conductors in "LINE CONSTANTS" (Sect. 7.4; II-3.) . . . 146
rroughs computer version of EMTP (Sect. 0.5m) . . . x-mn

ABLE CONSTANTS" request for transfer to it (Sect. 1.0g) . . . 4e
ABLE CONSTANTS" supporting routine (Sect. 7.7) . . . 251
pacitance modeling in the EMTP. See:
  Linear, single-phase representation (Sect. 1.21) . . . 6
  Linear, multi-phase [C] (Sect. 1.23) . . . 9
  For delta-connected transformer (Sect. 1.25, end) . . . 12j
  "LINE CONSTANTS" formulas (Sect. 7.4, II-2.2) . . . 144
rson's formula for "LINE CONSTANTS" (Sect. 7.4, App.) . . . 157
ASCADED PI" feature, for phasor solutions (Sect. 1.22) . . . 7
se title text of plotting (Sect. 1.10B, Point 1) . . . 40c
thode of valve/diode switch component (Sect. 1.43) . . . 30c
C (Control Data) version of EMTP (Sect. 0.5a) . . . x-a
HANGE PRINTOUT FREQUENCY" of DELTAT-loop (Sect. 1.0e10) . . . 4c
rcuit breaker modeling. See "Switches; ordinary".
LAMP" signal of TACS-controlled switch (Sect. 1.44) . . . 30f
LOSED" request of valve/diode card (Sect. 1.43, Rule 5) . . . 30d
axial cable parameters. See "CABLE CONSTANTS".
mment card, used in data case (Sect. 1.-a) . . . 1a

Compensation, number of phases (Sect. 0.6, List 24, NCOMP) xiii-2
Compensation technique of handling nonlinearities 17a
COMPLEX (FORTRAN) precision limits (Sect. 7.7.1, Restriction 2) 252
Computers. See "Installation dependent information".
Conductor card of "LINE CONSTANTS" (Sect. 7.4, Point 3) 116
Connectivity requirement of network solution:
   for phasor solution (Sect. 2.2b, Message 11) 47c
   for delta-connected transformers (Sect. 1.25, end) 12j
Contributors. See "Maintenance".
Control system modeling. See "TACS" 274
Controlled integrator, Type-58 TACS device (Sect. 8.5.5) 306
"CONVERT" routine for flux-current curve (Sect. 7.2) 101
Converter model, HVDC, Type-16 source (Sect. 1.61) 34a
Cray-1 computer version of EMTP (Sect. 0.5L) . . . . x-L
Current source modeling. See "Source cards".

Data General (DG) version of EMTP (Sect. 0.5e) . . . . x-e
DC converter. See "Converter", "valve", "TACS".
DC motor/generator modeling. See "Universal machine (U.M.)".
Debugging of problem solutions. See "DIAGNOSTIC".
Deionization time of valve (Sect. 1.43, Rule 4b) 30d
"DELTA CONNECTION" of S.M. armature windings (Sect. 1.62b, Class 2) 35e
"DELTAT" time-step size definition. See "Miscellaneous data".
Derivative, Type-59 TACS device (Sect. 8.5.5) 307
Devices of TACS control system modeling (Sect. 8.5.5) 298
"DIAGNOSTIC" printout for debugging (Sect. 1.0g7) 4c-7
Digital computers. See "Installation dependent information".
Digitizer, Type-55 TACS device (Sect. 8.5.5) 303
Diode switch component (Sect. 1.43) 30c
Disclaimer of any responsibility for misuse (Section 0.1) 1v
Distributed modeling. See "Transmission line".
Distribution of random numbers. See "STATISTICS".
Dollar-cards ($-cards) for special file operations (Sect. 1.-D) 3b
Dommel, Prof. Hermann W. See "Newsletter".
Double-circuit transmission line representation. See:
   Transposed model with zero sequence coupling (Sect. 1.26a) . . 15b
   Recursive convolution modeling (Sect. 1.27) 16c-1
Dube, Mr. Laurent Dube (Section 8.) 274
Dynamic limiter of TACS (Sect. 8.5.3) 289
Dynamic synchronous machine. See "Synchronous machine".

Earth wires of transmission lines. See "Ground wires".
Ebasco Services, Inc. See "Burroughs computer version".
Education of program users (See Section 0.) iv
Empirical specification of EMTP sources (Sect. 1.9b) 39
Equivalent-Pi of "LINE CONSTANTS" by doubling (Sect. 7.4, App. 6) 186
Error messages of program; fatal ones (Sect. 2.4) 50
Exciter modeling for generators (Sect. 1.62a, Class 6, Rule 1) . . 34h
Exponential tails. See "Tails of weighting functions".
Exponentials of recursive convolution (Sect. 1.27) 16c-1
Extensions to misc. data cards (Sect. 1.1) 5
Extrema of solution variables. See:
   Request MAXOUT of misc. data (Sect. 1.0h) 4g
   "BEGIN PEAK VALUE SEARCH" for delay (Sect. 1.0e11) 4c
   "PEAK VOLTAGE MONITOR" for 1 peak node volt. (Sec. 1.0e13) . . 4c-2
   "STATISTICS" for use in Monte Carlo studies.
Fatal error messages. See "Error messages".

FGH of Mannheim, West Germany. See "Siemens computer version".
"FINISH" card for S.M. TACS connections (Sect. 1.62a, Class 6) 34h-2
Fixed-dimension limits temporarily in program:
  Multi-phase ZnO surge arresters 17h
  Dynamic synchronous machine (S.M.) sources 36c
  "CABLE CONSTANTS" routine (Sect. 7.7.1, Restriction 1) 251
Flashover (or spark) gap. See:
  Flashover switch (Sect. 1.40, Class 2) 27
  Type-99 pseudo-nonlinear resistance (Sect. 1.28) 16d
  Sect. 1.35 onward for use with compensation-based elements
Format specifications for data; general (Sect. 0.7) xviii
Free-format of TACS supplemental variables (Sect. 8.5.5-A) 296
"FREE FORMAT" request to redefine characters (Sect. 1.0g6) 4e-6
Free-format usage, general. See "Format specifications".
Frequency card of "LINE CONSTANTS" (Sect. 7.4, Point 4) 121
Frequency-dependent parameter representation. See:
  Recursive convolution, "SEMLYEN SETUP", "HAUER SETUP",
  "WEIGHT" or weighting functions, "AMETANI SETUP"
Frequency meter, Type-50 TACS device (Section 8.5.5) 299
"FREQUENCY SCAN", to loop over phasor solutions (Sect. 1.0g3) . . 4e-2
Function block of TACS (Sect. 8.5.1) 286

Gain of TACS transfer function block (Sect. 8.5.1) 286
Gap, as TACS-controlled EMTP switch type (Sect. 1.4) 26
Graphical output. See "Plotting of EMTP results."
"GRID" firing signal of valve (Sect. 1.43) 30c
Ground (local) of electric network, blank name (Sect. 1.-b) . . . 1a
Ground wires of "LINE CONSTANTS" (Sect. 7.4, cond. card, IPHASE) 116
Ground modeling. See "Carson", "Nakagawa".

Harris computer version of EMTP (Sect. 0.5g) . . . . x-g
"HAUER SETUP" routine for transfer to it (Sect. 1.0g) 4e
"HAUER SETUP" supporting routine (Sect. 7.8) 271
"HEIGHT" adjustment for plot (Sect. 1.10B, Point 6) 41
Hewlett-Packard version of EMTP (Sect. 0.5i) . . . . x-i
Holding current of valve/diode (Sect. 1.43, IHOLD) 30c
Honeywell version of EMTP (Sect. 0.5d) . . . . xii-a
HVDC. See "Converter", "Valve", "TACS".
Hysteresis modeling, magnetic. See
  Branch cards for Type-96 reactor (Sect. 1.31) 16L
  "HYSDAT" routine to generate characteristic (Sect. 7.2a) . . . 103b

IBM version of EMTP (Section 0.5b) . . . . x-b
IF-component, Type-60 TACS device (Sect. 8.5.5) 307
Ignition voltage of valve (Sect. 1.43, Rule 4a) 30d
Illustration of usage. See "Sample EMTP simulation."
Induction machine modeling using U.M. (Sect. 1.63a) 36g-4
Initial condition specification for EMTP variables. See:
  Cards to over-ride electric network initial cond. (Sect. 1.7) 37
  Cards to specify (no over-ride) TACS init. cond. (Sect. 8.5.7) 308
Input supplemental variables (Type 99) of TACS (Sect. 8.5.5) 295
Inside supplemental variables (Type 88) of TACS (Sect. 8.5.5) 295
Input/output unit numbers of EMTP (Sect. 0.5) viii-5
Installation-dependent information (Sect. 0.5) viii
  General, for all computer systems of interest viii
  Specific computer systems (Sect. 0.5a to 0.5q) . . . . x-a
Instantaneous min/max, Type-63 TACS device (Sect. 8.5.5) 310
Insulator layers of "CABLE CONSTANTS" (Sect. 7.7.1) 251

Interactive CRT plotting of EMTP results (Sect. 5.0A) 86
Interpretation of input data cards (Sect. 2.1) 44
Introductory information (Section 0.) iv

Japanese EMTP Committee (Sect. 0.5p) . . . . x-p
Japanese computer versions of EMTP (Sect. 0.5p) . . . . x-p

Karrenbauer transformation for transposition (Sect. 4.1) 82
KILL code number of error stops. See "Error messages".

LABORELEC of Rhode-St-Genese, Belgium. See "SEL version".
Lawrence Livermore Laboratory. See "Cray-1 version".
Leakage inductance from self and mutual, for U.M. (Sect. 1.63) . 36k-2
Level-triggered switch, Type-51 TACS device (Sect. 8.5.5) 300
Library functions, FORTRAN-like, of TACS (Sect. 8.5.5) 296
Light house keeper. See "Dube", "TACS".
Lightning arrester modeling. See "Surge arrester".
"LIMASS" limit on S.M. shaft masses (Sect. 1.62a, Class 5) . . 35q
"LIMIT ON PLOT OSCILLATIONS" for averaging (Sect. 1.0c, NSMTH) . 4a-1
Limiters for control variables of TACS (Sect. 8.5.3) 289
"LINE CONSTANTS" request for transfer to it (Sect. 1.0g) 4e
"LINE CONSTANTS" supporting routine (Sect. 7.4) 113
List sizes. See "Variable dimensioning".
Logical (Boolean) operators of TACS (Sect. 8.5.5-A) 296

Machinery modeling. See "Rotating machinery".
Madison. See "University of Wisconsin".
Magnetizing current or impedance of transformer. See
Saturable "TRANSFORMER" component (Sect. 1.25, Rule 2) 12e
Linear "XFORMER" specification (Sect. 7.1) 94
Linear "TRELEG" specification (Sect. 7.1a) 100b
Maintenance of program (Section 0.2) . . . . iv-a
Matrix inversion/reduction formulas. See "Shipley".
Memoranda, EMTP, Ref. 8 of Sect. 0.4 References vi
Metric CalComp plotting via "SCALE" (Sect. 1.10B, Point 14) . . . 43e
"METRIC" option of "LINE CONSTANTS" (Sect. 7.4) 114
Minicomputers. See "VAX", "PRIME", etc.
Min/max tracking, Type-64 TACS device (Sect. 8.5.5) 310
Minnesota Power & Light. See "PRIME version".
"MISCELLANEOUS DATA CARDS" by special request (Sect. 1.0e9) . . . 4b-6
Miscellaneous data cards of simulation case (Sect. 1.0h) 4f
Modal analysis theory of "LINE CONSTANTS" (Sect. 7.4, II-4.) . . 149
MODCOMP computer version of EMTP (Sect. 0.5o) . . . . x-o
"MODE VOLTAGE OUTPUT" for Karrenbauer modes (Sect. 1.0f) 4d
"MODIFY DELTAT" to alter time-step size (Sect. 1.0g5) 4e-4
Murphy's Law. See any section.
Monte Carlo studies. See "STATISTICS".

Nakagawa. See "Stratified earth model".
Newsletter (EMTP Newsletter; Section 0.) iv
Node names of electric network (Sect. 1.-a) 1a
Node voltage output specification (Sect. 1.8a) 38
Non-fatal informative messages (Sect. 2.2b) 46a-1
Nonlinear elements. See "Resistance", "Reactance", etc.

"OMIT BASE CASE" of STATISTICS run (Sect. 1.0e8) 4b-6
Ontario Hydro. See "Univac", Sect. 0.5c .
"OPEN/CLOSE" signal of valve (Sect. 1.43, Rule 4c) 30d

Output supplemental variables (Type 98) of TACS (Sect. 8.5.5) . . 295

"PARAMETER FITTING" of S.M. data (Sect. 1.62a, Class 2) 34e-3
Parenthesis usage for TACS grouping (Sect. 8.5.5-A, Rule 4) . . . 297
Parks equations for rotating machine (Sect. 1.62a, beginning) . . 34e-1
PDP-10 computer version of EMTP (Sect. 0.5k) . . . . x-k
Peak values of solution variables. See "Extrema".
"PEAK VOLTAGE MONITOR" for peak node voltage (Sect. 1.0e13) . . 4c-2
"PEN CHOICE" and grid status of plot (Sect. 1.10B, Point 11) . . . 43
Phasor solution for initial conditions. See
  Electric network printout (Sect. 1.0h, KSSOUT=1) 4j
  Control system TACS usage (Sect. 8.4, Point 6) 285
Pi-circuit branch component (Sect. 1.23) 8
Pipe-type cables. See "CABLE CONSTANTS".
Plots of "STATISTICS" switch closing times (Sect. 1.8b, end) . . 38d
Plotting of EMTP results. See
  Batch-mode plot card data requirements (Sect. 1.10) 40
  Interactive CRT plotting (Sect. 5.) 86
Point-by-point nonlinearity, Type-56 TACS device (Sect. 8.5.5) . 304
"POSTPROCESS PLOT FILE" using TACS (Sect. 1.0e17) 4c-6
Potential coefficient matrix [P] (Sect. 7.4, App. 1-b) 170
"POWER FREQUENCY" (system frequency) change (Sect. 1.0c, STATFR) 4a-2
Power output of branch or switch (Sect. 1.8a) 38a
PRIME version of EMTP (Sect. 0.5f) . . . . x-f
"PRINT HEAD" usage for plot lettering (Sect. 1.10B, Point 10) . 42
Printout of time-step loop. See:
  Variable IOUT of miscellaneous data (Sect. 1.0h) 4f-1
  "CHANGE PRINTOUT FREQUENCY" request (Sect. 1.0e10) 4c
  Output variable specification (Sect. 1.8) 38
Program Maintenance (Sect. 0.2) . . . . iv-a
Pseudo-nonlinear element modeling of EMTP. See:
  Type-96 hysteretic inductor (Sect. 1.31) 16L
  Type-98 nonlinear reactor (Sect. 1.29) 16g
  Type-99 nonlinear resistor (Sect. 1.28) 16d
Pulse delay, Type-54 TACS device (Sect. 8.5.5) 302
Punched card output of EMTP (Sect. 0.5-5., LUNIT7) viii-5

Random number generator testing (Sect. 1.1a, Point 3) 5c
Reactor modeling. See:
  for linear case, use series R-L-C branch (Sect. 1.21) 6
  pseudo-nonlinear branch card, Type-98 (Sect. 1.29) 16g
  1-phase true nonlinear reactor, Type-93 (Sect. 1.37) 24
Recursive convolution frequency dependence (Sect. 1.27) 16c-1
Reference manual: former name for this work (Rule Book).
Reference material (supporting literature; Sect. 0.4) vi
References of "LINE CONSTANTS" (Sect. 7.4, end) 189
Relational operators (e.g., "EQ") of TACS (8.5.5-A) 296
"RELATIVE TACS DIMENSIONS" to size TACS tables (Sect. 1.0e5) . . 4b-3
"RELATIVE U.M. DIMENSIONS" to size U.M. tables (Sect. 1.0e14) . . 4c-3
Relay-operated switch, Type-51 TACS device (Sect. 8.5.5) 300
"RENUMBER BYPASS" request, to keep input order (Sect. 1.0g4) . . 4e-3
Residual flux of reactor. See:
  Type-93 switched-inductor usage (Sect. 1.41, Rule 4) 29
  Type-96 hysteretic-inductor use (Sect. 1.31, Rule 5) 16h
Resistance (resistor) modeling of EMTP. See:
  Uncoupled, linear R-L-C branch (Sect. 1.21) 6
  Multi-phase, linear [R] (Sect. 1.24) 12
  Zinc-oxide surge arrester (Sect. 1.32) 17

  Type-99 pseudo-nonlinear resistor (Sect. 1.28) 16d
  Type-92 true nonlinear, 1-phase (Sect. 1.36) 21
Restrike modeling of breakers. Use TACS (Sect. 8.) 274
Revision date of Rule Book. See front cover.
Rotating machinery modeling. See
  3-phase dynamic synchronous machine (Sect. 1.62) 34d
  Universal machine model (Section 1.63) 36f
"SAME" request of valve/diode model (Sect. 1.43, Rule 6) 30d
Sample and track, Type-62 TACS device (Section 8.5.5) 309
Sample EMTP simulation, annotated output (Sect. 2.3) 49b
"SATURATION" request for transfer to "CONVERT" (Sect. 1.0g) 4e
Saturation effects, data, modeling. See:
  "Reactors" for modeling of saturable reactor.
  "CONVERT" for reactor saturation curve derivation
  for S.M. modeling (Sect. 1.62a, Class 3, AGLINE, S1, S2) . . 34e-6
  for U.M. modeling (Sect. 1.63, Class 2, JSATD, LMSD) 36j-2
S-block. See "Function block of TACS".
Screening matrix of "LINE CONSTANTS" (Sect. 7.4, II-8) 164
Segmented ground wires in "LINE CONSTANTS" (Sect. 7.4, II-8.) . . 165
SEL (Systems Engineering Laboratories) version (Sect. 0.5n) . . x-n
"SEMLYEN SETUP" request for transfer to it (Sect. 1.0g) 4e
"SEMLYEN SETUP" supporting routine (Sect. 7.5) 201
Sheath of "CABLE CONSTANTS" (Sect. 7.7.1) 251
Shipley matrix reduction/inversion formula (Sect. 7.4, App. 4) . . 180
Short Course. See "Education ....".
Siemens computer version of EMTP (Sect. 0.5q) . . . . x-q
Signal selector, Type-61 TACS device (Sect. 8.5.5) 308
Signal sources of TACS; TACS sources (Sect. 8.5.4) 292
Silicon-carbide. See "Surge arrester"
Singularity tolerances. See:
  For network, Miscellaneous data (Sect. 1.0h, EPSILN, TOLMAT) . 4f
  ZnO surge arrester soln. (Sect. 1.32, end) 17h
  Type-50 S.M. equations (Sect. 1.62b, Class 2-b, EPDGEL) . . . 35f
Sinusoidal steady state. See "Phasor solution".
Skin effect formulas of "LINE CONSTANTS" (Sect. 7.4, App. 2) . . 171
"SMOOTH" parameter of plotting (Sect. 1.10-A, Rule 8) 40a1
Smoothing of plotting by averaging. See "LIMIT ON PLOT OS..".
Source cards of electric network (Sect. 1.6) 31
Source cards of TACS (Sect. 8.5.4) 292
Spark gap. See "Flashover gap".
"SPARK" signal of TACS-controlled switch (Sect. 1.44) 30f
Special request cards at beginning of data case (Sect. 1.0) . . 3c
"START AGAIN" request to restart halted run (Sect. 1.0e15) . . . 4c-4
Statistical overvoltage studies. See
  Output variable specification (Sect. 1.8b) 38c
  "STATISTICS" miscellaneous data (Sect. 1.1a) 5
  "STATISTICS" output specification (Sect. 1.8b) 38c
  "STATISTICS OUTPUT SALVAGE" request card (Sect. 1.0e7) 4b-5
  "STATISTICS" switch (Sect. 1.4, Class 3a) 27a-1
  "TABULATE ENERGIZATION RESULTS" request card (Sect. 1.0e6) . . 4b-4
  "TIME OF DICE ROLL" request card (Sect. 1.0e12) 4e-1
"STATISTICS OUTPUT SALVAGE" to save results (Sect. 1.0e7) . . . 4b-5
Steady-state phasor solution, explanation, KSSOUT (Sect. 1.0h) . . 4j
Stratified earth model of "CABLE CONSTANTS" (Sect. 7.7) 267
Structure of EMTP database (Section 1.) 1
Summer (zero-th order function) of TACS (Sect. 8.5.2) 288

"SUPERIMPOSE" for multi-scale plots (Sect. 1.10B, Point 13) 47a
Supplemental variables of TACS (Sect. 8.5.5) 295
Supporting routines (Sect. 7.) 93a
Surge arrester modeling. See
  Multi-phase, exponential ZnO model (Sect. 1.32). 17
  1-phase, SiC model with active gap 25a
  Pseudo-nonlinear Type-99 resistor (Sect. 1.28) 16d
  1-phase true nonlinear resistor (Section 1.36) 21
  1-phase, continuous, time-varying resistor (Sect. 1.35) . . . 19
Surge function, Type-15 source component (Sect. 1.6) 33
Switches and switched-element modeling:
  Introduction and overview (Sect. 1.4) 26
  Ordinary switches (time-controlled, flashover,
    "STATISTICS", "SYSTEMATIC" ; Sect. 1.40) 26a
  Switched-inductance element, Type 93 (Sect. 1.41) 29
  Switched-resistance element, Type 92 (Sect. 30a) 30a
  Diode and valve modeling, Type 11 (Sect. 1.43) 30c
  Spark gap and TRIAC modeling, Type 12 (Sect. 1.44) 30f
Symmetrical component quantities. See:
  "LINE CONSTANTS" theory (Sect. 7.4, Subsect. 5.) 154
  Format for [R], [L] branch input (Sect. 1.24) 12b
Synchronous machine (S.M.) modeling:
  General recommendations (Sect. 1.62) 34d
  Brandwajn (Type-59) modeling (Sect. 1.62a) 34d-2
  SCE (Type-50) modeling (Sect. 1.62b) 35
  Altering fixed S.M. table sizes (Sect. 1.62b, end) 36c
  using U.M. modeling (Sect. 1.63c) 36L
"SYSFIT" routine (overlay) of "HAUER SETUP" (Sect. 7.8.1.2) . . . 271a
"SYSTEMATIC" switches. See "STATISTICS"
SYSTEM20 (DEC) computer version of EMTP. See "PDP-10 version".

Table of Contents i
"TABULATE ENERGIZATION RESULTS" to combine parts (Sect. 1.0e6) . 4b-4
TACS (EMTP control system modeling capability). See:
  Rules for data assembly and operation (Sect. 8.) 274
  Card to introduce TACS data (Sect. 1.20) 5e
  "ABSOLUTE TACS DIMENSIONS" request card 43b-2
TACS-controlled switch. See "Valve".
TACS-controlled voltage or current source (Sect. 1.6, Type 60) . . 33
"TACS EMTP SOURCES" request for Type 1-10 sources (Sect. 1.0g2) . 4e-1
"TACS HYBRID" request preceding TACS data (Sect. 1.20) 5e
"TACS STAND ALONE" request preceding TACS data (Sect. 1.20) . . . 5e
Tails of weighting functions (Sect. 1.26b) 16b
Telefunken version of EMTP (Sect. 0.5h) . . . . z-h
Thyrister modeling. See "Valve".
"TIME OF DICE ROLL" for table-saving time (Sect. 1.0e12) 4c-1
Time-sequenced switch, Type-57 TACS device (Sect. 8.5.5) 305
"TIME STEP LOOP" request follows "START AGAIN" (Sect. 1.0e16) . . 4c-5
Time-step size (misc. data, DELTAT, Sect. 1.0h) 4f
Time-varying resistance elements. See:
  Type-97 staircase resistance (Sect. 1.30) 16j
  Type-91 continuous resistance (Sect. 1.35) 19
"TMAX" termination time definition. See "Miscellaneous data".
Transfer function of control system. See "Function block".
Transformer modeling. See
  Saturable "TRANSFORMER" component (Section 1.25) 174
  Linear coupled R-L model (Section 1.24) 12
  Supporting program to derive R-L model (Sect. 7.1) 93b
  Refer also to nonlinear reactor modeling for saturation

Transmission line modeling. See
  Pi-circuit model (Section 1.23) 8
  Continuously-transposed, distributed model (Section 1.26) . . 13
  Untransposed, frequency-dependent model (Section 1.27) . . . 16c1
  Supporting programs (Sect. 7.4 to 7.8) 93a
Transport delay, Type-53 TACS device (Sect. 8.5.5) 301
Transposition of lines, mathematics (Sect. 7.4, App. 5) 183
"TRASH" node of Type-16 source (Sect. 1.61, Rule 7) 34c
"TRELEG" routine for core-type transformers (Sect. 7.1a) 100a
TRIAC. See "Switches".
"TYP-16" node of Type-16 source (Sect. 1.61, Rule 7) 34c

U.M. See "Universal Machine".
Univac version of EMTP (Section 0.5c) . . . . x-c
Universal machine (U.M.) modeling (Sect. 1.63) 36f
University of British Columbia (Sect. 0.) iv
University of Minnesota. See "CDC".
University of Pittsburgh. See "PDP-10 version".
University of Wisconsin. See "Education", "Harris".
"USE AB" option for Pi-circuits (Sect. 1.23, Rule 8) 11
"USE RL" option for Pi-circuits (Sect. 1.23, Rule 10) 11
User instruction. See "Education".
User's Manual: former name for this work (Rule Book)

Valve (thyrister) switch component (Sect. 1.43) 30c
Variable dimensioning of EMTP tables (Sect. 0.6) xiii
VAX version of EMTP (Section 0.5j) . . . . x-j
Voltage regulator modeling. See "Exciter modeling".
Voltage source modeling. See "Source cards", "Rotating machinery".

"WEIGHT" routine to derive weighting functions (Sect. 7.3) . . . 104
"WEIGHTING" request for transfer to "WEIGHT" (Sect. 1.0g) . . . 4e
Weighting function usage with branch cards (Sect. 1.26b) . 16a

"X-Y PLOT" with time as parameter (Sect. 1.10B, Point 15) . . . 43e
"XFORMER" request for transfer to "XFORMER" (Sect. 1.0g) 4e
"XFORMER" routine for transformer [R], [L] (Sect. 7.1) 93b

Z-block of TACS. See "Summer".
Zinc-oxide surge arrester modeling
  Branch card data input (Sect. 1.32) 17
  Supporting routine "ARRDAT" to fit exponentials (Sec. 7.2b) . 103h
  Type-17 voltage-dependent current source (Sect. 1.6) 33

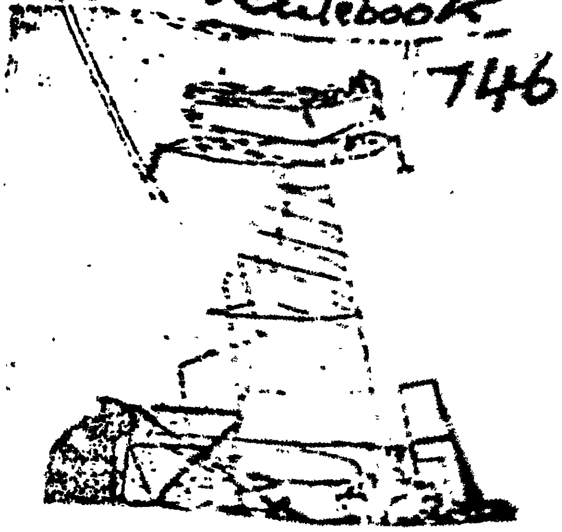
Last-minute, out-of-order additions to table of contents

Fourier analysis of EMTP variables (Sect. 1.10, Rule 6, Point 16) 43h
Harmonic content of signals. See "Fourier analysis".
Spectral analysis. See "Fourier analysis."

Update for Sept. 1980 Rulebook
3-2-82

746

1.26 Branch Cards for Distributed-Parameter Transmission Lines



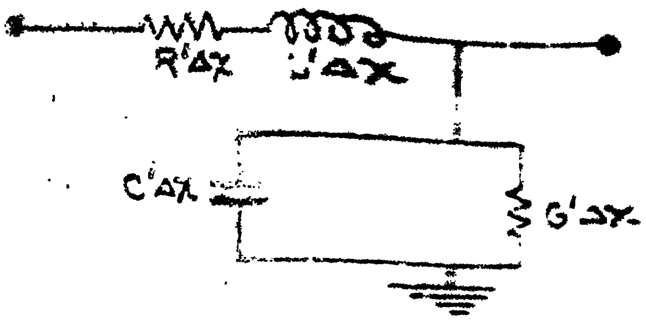
General Comments

The modelling used to represent transmission lines in the Transients Program poses a number of possibilities for the user.

To start the analysis, one can write the "exact" partial differential equations governing the voltage and current on the line. For N phases (conductors), these are

$$-\frac{\partial \vec{v}}{\partial x} = [L]\frac{\partial \vec{i}}{\partial t} + [R]\vec{i}$$

$$-\frac{\partial \vec{i}}{\partial x} = [C]\frac{\partial \vec{v}}{\partial t} + [G]\vec{v}$$



Incremental section, [illegible] = Δx

Although the incremental section of line has been sketched only for N=1, in general these are vector-matrix equations, where [L], [R], and [C] can be determined from a line-constants program. See "LINE CONSTANTS" of Sect. 7 4 .

Now if the transmission line is assumed to be transposed (or just balanced, if 2-phase), then all matrices have only two distinct element values: all diagonals have a common value "S", and all off-diagonals have a common value "M".

"S" ⇒ Self

"M" ⇒ Mutual

S	M	M
M	S	M
M	M	S

But if such a transposition assumption is not realistic for the study contemplated, two options are now available. For a long time, the only option was to cascade lumped-parameter Pi-sections, each of which approximately represents the actual construction over the maybe 20 or so miles of the section. Yet such a lumped-parameter solution is costly in computer time and storage requirements, so should be avoided if practical.

In December, 198[illegible], the option of modeling the line as untransposed was implemented in the EMTP with the help of Dr. K. C. Lee of the University of British Columbia in Vancouver, B.C, who originally developed this modeling capability (see Reference 30).

Untransposed lines

For an untransposed transmission line, the self impedances (capacitances) of all phases as well as their mutual impedances (capacitances) are no longer equal among themselves. However, the line constants matrices are still symmetric. Modal decoupling is still possible, but the transformation matrices required for the diagonalization process are now characteristic of the line configuration, and must be supplied by the user. The diagnoal matrices $[Z'_{mode}]$ and $[C'_{mode}]$ in the modal domain are obtained from

$$[Z'_{mode}] = [Tv]^{-1} \; [Z'_{phase}] \; [Ti]$$

$$[C'_{mode}] = [Ti]^{-1} \; [C'_{phase}] \; [Tv]$$

where $[Ti]^{-1} = [Tv]^{t}$,

with the columns of [Tv] being the eigenvectors of the matrix product $[Z'_{phase}]$ $[jwC'_{phase}]$. Voltages and currents in phase quantities are obtained from modal quantities with [Ti] and [Tv] as follows:

$$[i_{phase}] = [Ti] \; [i_{mode}] \; ,$$

and

$$[v_{phase}] = [Tv] \; [v_{mode}] \; .$$

Inpute data for untransposed transmission lines must be given in modal quantities, i.e., N sets of values R'_{mode} , L'_{mode} and C'_{mode} must be specified on the N cards of an N-phase line. These N cards are followed by cards for the modal transformation matrix [Ti]. This modal transformation matrix [Ti] for the currents as well as the branch cards for the untransposed line are now automatically generated on unit LUNIT7 when one runs "LINE CONSTANTS" of the EMTP.

Theoretically, the transformation matrix [Ti] is complex as well as frequency-dependent. For overhead lines, however, it was found that the matrix [Ti] can be approximated by a real-valued and frequency-independent matrix over a frequency rnage from 10 Hz to 10 kHz with sufficient accuracy.[1]

An example of branch cards and transformation matrix generated on LUNIT7 is shown below. This is the result of running "LINE CONSTANTS" of an untransposed Coulee-Raver double circuit line of 124.74 miles long.

```
ITYPE                              R          Zs          v        DIST      ILINE  No. of phases
-1                        0.39795E+00 0.14213E+04 0.14925E+06-0.12427E+03 1 6
-2                        0.62950E-02 0.64283E+03 0.18532E+06-0.12427E+03 1 6
-3                        0.59578E-02 0.43360E+03 0.18600E+06-0.12427E+03 1 6
-4                        0.60542E-02 0.44213E+03 0.18594E+06-0.12427E+03 1 6
-5                        0.37393E-02 0.23887E+03 0.18596E+06-0.12427E+03 1 6
-6                        0.37447E-02 0.23942E+03 0.18596E+06-0.12427E+03 1 6
 0.38738E+00-0.35219E+00-0.51256E+00-0.51568E+00-0.36241E+00-0.10218E+00 ┐
 0.37287E+00-0.37470E+00-0.65305E-01 0.95222E-02 0.70548E+00 0.21915E+00 │
 0.46217E+00-0.47703E+00 0.44612E+00 0.52051E+00-0.33732E+00-0.10066E+00 ├ [Ti]
 0.37923E+00 0.32012E+00 0.54461E+00-0.49304E+00 0.12492E+00-0.36837E+00 │
 0.37364E+00 0.37165E+00 0.68424E-01-0.23715E-01-0.21558E+00 0.69893E+00 │
 0.46651E+00 0.51065E+00-0.48001E+00 0.46726E+00 0.83463E-01-0.34651E+00 ┘
```

where R is the modal resistance, Zs is the modal surge impedance, v is the modal speed of propagation, and DIST is the length of the line(with extra minus sign appended).

A few things should be noted here:

1) The branch data on LUNIT7 are generated with the higher-precision format, so a $VINTAGE, 1 card must be added before the first branch card and a $VINTAGE, 0 card needs to be added after the last branch card (see p.15a-1).

2) On each branch card, the user must punch the 6-character bus names of the branch. The format is 2A6 in columns 3 to 14. Both the $VINTAGE cards and bus names of the branchs will be automatically generated for the user in the future.

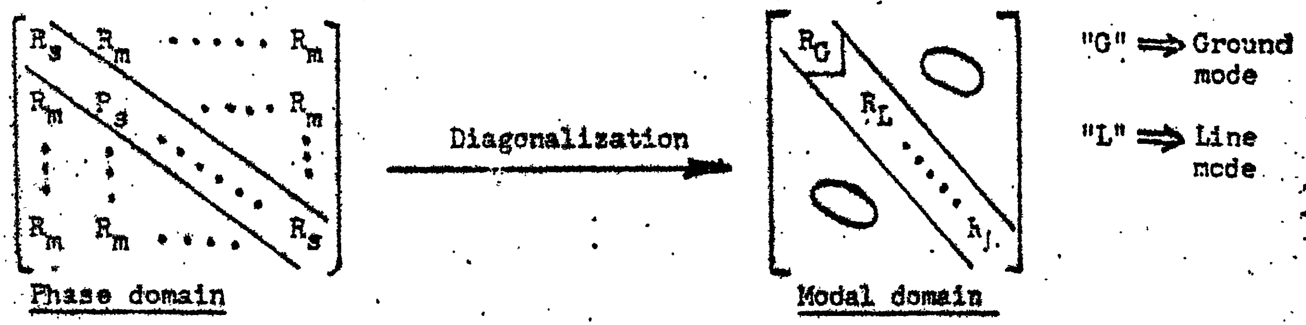
3) The negative sign on the length of the line is a flag for EMTP to recognize it is an untransposed line when this format is used.

4) Real-valued transformation matrix [Ti] elements use 6E12.5 format.

5) The user also has the option of inputting these branch cards with the regular format described on p.14 and 15.

Transposed lines

The original modeling of the continuously transposed distributed parameter line can now be viewed as a special case of the untransposed line modeling, where the former has only two distinct matrix elements. The N mutually-coupled variables in the phase domain can again be converted to N equivalent uncoupled modes be the aforementioned transformation matrices [Tv] and [Ti]. However, for a transposed line, there are only two distince modes --- a zero-sequence(ground) mode and (N-1) identical positive-sequence(line) modes.



Similar relations apply to [L] and [C].

Until now, the Karrenbauer's transformation was used in the EMTP to diagonalize the matrices for a transposed line. However, one key characteristic of the Karrenbauer transformation, [Tv] = [Ti], is not generally valid for an untransposed line. Rather than have two different sets of logic for the conversion of variables between phase and modal domains, it was decided to treat the transposed line as just a particular special case of the untransposed one. In both cases, the conversion formula given on the last page is used. To accomplish this, a more general transformation matrix has now been chosen to replace the originally-used Karrenbauer transformation. This new transformation matrix [Ti] was first used in the EMTP by Ontario Hydro, in the "SEMLYEN SETUP" code of Section 7.5. It has the following form:

$$[T_i] = \begin{array}{c|ccccccc|}
 & & & & & \text{J-th col.}\downarrow & & \\
 & \frac{1}{\sqrt{N}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{6}} & \cdots & \frac{1}{\sqrt{J(J-1)}} & \cdots & \frac{1}{\sqrt{N(N-1)}} \\
 & \frac{1}{\sqrt{N}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{6}} & \cdots & \frac{1}{\sqrt{J(J-1)}} & \cdots & \frac{1}{\sqrt{N(N-1)}} \\
 & \frac{1}{\sqrt{N}} & 0 & -\frac{2}{\sqrt{6}} & & \vdots & & \vdots \\
 & \vdots & \vdots & 0 & & \vdots & & \vdots \\
\text{J-th row}\rightarrow & \vdots & \vdots & \vdots & & -\frac{(J-1)}{\sqrt{J(J-1)}} & & \vdots \\
 & \vdots & \vdots & \vdots & & 0 & & \vdots \\
 & \frac{1}{\sqrt{N}} & 0 & 0 & & 0 & & -\frac{(N-1)}{\sqrt{N(N-1)}}
\end{array}$$

where N is the number of phases of the line.

When N=1, [Ti]=1. This corresponds to a single-phase transmission line which is mathematically identical with its zero sequence (i.e. transformation produces no change), this special case simply hs no positive-sequence values; only zero sequence data is inputted.

Such a transformation matrix [Ti] is generated by the EMTP right after each continuously-transposed line is inputted. From then on, there is no difference in the EMTP in treatment of untransposed and transposed lines, as far as the conversion logic between phase and modal domains is concerned. Removal of the Karrenbauer transformation and its associated logic resulted in a reduction of about 350 lines of EMTP FORTRAN. This, however, does not change the original input format for the transposed line, nor does it change the results of physical variables (i.e., phase voltages and currents should be identical).

Distortionless line modelling

A transmission-line mode is well known[7] to be distortionless if parameters for that mode satisfy the relation $R'/L' = G'/C'$. Of course actual leakage conductance for an overhead line is very nearly zero, and no provision for inputting a nonzero value is provided by this program anyway. If the user wants distortionless-line modelling, it is presumed that the input value of R' is meant to be a measure of the total line losses. Therefore the program splits the losses into series and shunt losses by computing the series resistance R'_{series} and the leakage conductance G'_{leak} from the relation

$$\frac{R'_{series}}{L'} = \frac{G'_{leak}}{C'} = 0.5\left(\frac{R'}{L'}\right)$$

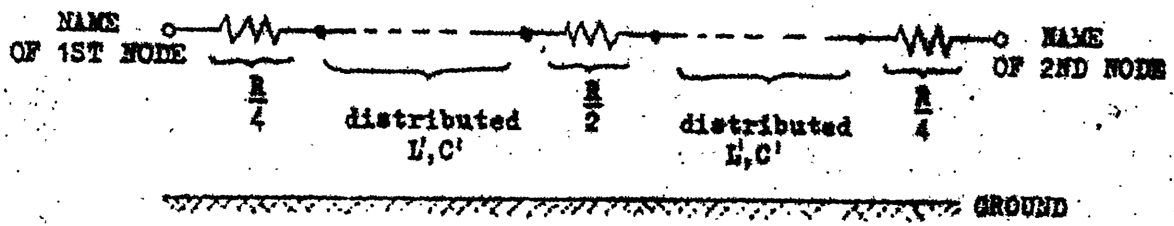
With this formula, the ac steady-state results are practically identical whether the line is modelled as distortionless or in the other two ways to follow. Transient responses differ mainly in the initial rise of voltage pulses. The attenuation constant α is found from the relation

$$\alpha = \frac{1}{2} \cdot \frac{R'}{L'} \cdot \sqrt{L'C'} = \frac{1}{2} \frac{R'}{Z}, \text{with } Z = \sqrt{\frac{L'}{C'}}.$$

The corresponding decrement factor is $e^{-\alpha \ell}$, where ℓ is the line length. Such distortionless modelling is generally used only for the positive sequence, if at all.

Lumped-resistance line modelling

The second (and only other) distributed model which is readily solvable is that in which the series resistance is pulled outside of the distributed line, and represented as a lumped element. This is the most common representation used in BPA studies, the standard representation which is assumed unless the user specifically requests otherwise (see variable IPUNCH, cols. 53-54). The program automatically cuts the line in two, inserting half of the resistance in the middle, and one fourth at each end:



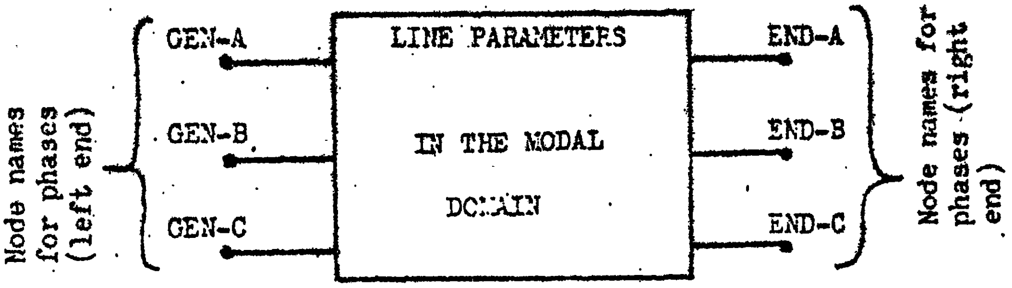
The half-length distributed sections then become lossless (hence distortionless, with attenuation $\alpha = 0$). Both modes of most lines in BPA studies are usually so represented at present. See further comments in Section 4.2 .

Frequency-dependent modelling

The resistance and inductance of the zero-sequence mode are typically quite variable with frequency; the resistance in particular, which is furthermore substantially larger than for the positive-sequence mode. "Exact" distributed-parameter representation is now available for the zero sequence, as described in Section 1.26b .

Data format for distributed-parameter line cards

To specify an N-conductor, distributed-parameter transmission line, conform to the following rules and format:


Node names for phases (left end)
GEN-A
GEN-B
GEN-C
LINE PARAMETERS
IN THE MODAL
DOMAIN
END-A
END-B
END-C
Node names for phases (right end)

Rule 1: Number the phases -1, -2, -3, ... , -N . Make out one branch card for each phase, and stack them in this sequence. Indicate this sequence by punching -1, ... -N in columns 1-2 of these cards (field ITYPE). N cannot exceed 9 phases.

Rule 2: Specify each of the phases -1, ... , -N by the names of the nodes at both ends (columns 3-14; field names BUS1, BUS2). Nodes may be grounded (indicated by blank name field) if desired.

Rule 3: If the parameters for this line are identical to those of another N-phase line previously inputted, then the option of rule 4 in section 1.23 may be used, except that no storage is saved here. Columns 15-26 with field names BUS3 and BUS4 are used in this case. Otherwise, they are left blank.

Rule 4: For an N-phase continuously-transposed line, there exists only two modes. Specify the zero-sequence parameters on the first card (the card for the first phase), and the positive-sequence parameters on the second card (the card for the second phase). Leave the modal parameters blank on the third and later branch cards. For an N-phase untransposed line, there exists N different modes. Specify the modal parameters for the first mode on the first card, and those for the second mode on the second card, etc. for the the third and later modes. The four basic pieces of modal information needed are resistance, inductance, capacitance, and length; yet three forms for this input are possible:

a) In all cases, punch resistance R' in ohms per unit length in columns 27-32, and line length ℓ in consistent units in columns 45-50.

b) Parameter ILINE (columns 51-52) determines how L' and C' may be disguised. Remember that variables XOPT and COPT come from the floating-point (first) miscellaneous data card of Section 1.0h .

ILINE	"A" ---- columns 33-38	"B" ---- columns 39-44
0	L' in mH/length if XOPT = 0 Reactance $\omega L'$ in Ω/length at frequency XOPT if XOPT $\neq$ 0	C' in μF/length if COPT = 0 Susceptance $\omega C'$ in μ mho/length at frequency COPT if COPT $\neq$ 0.
1	Surge impedance Z_s in ohms $Z_s = \sqrt{L'/C'}$	Propagation velocity in length/sec $v = 1/\sqrt{L'C'}$
2	Surge impedance Z_s in ohms $Z_s = \sqrt{L'/C'}$	Travel time τ of line, in sec $\tau = \ell / v = \sqrt{L'C'}\,\ell$

Rule 5: Output options for printing and/or plotting use a column-80 punch (variable IOUT). Only for a single-phase line is branch-current output possible. Within this restriction, though,

$$\text{IOUT} = \begin{cases} 1 \Rightarrow \text{branch current output only} \\ 2 \Rightarrow \text{branch voltage output only} \\ 3 \Rightarrow \text{both branch current and voltage output} \end{cases}$$

A blank or zero will give you no such output, of course.

Rule 6: All modes of a line must have travel time τ in excess of the time step size Δt (Sect. 1.0b). If not, the program will stop with an error message (see Section 2.4).

Rule 7: Both L' and C' must be nonzero for each mode.

Rule 8: Variable IPUNCH of columns 53-54 specifies the type of modelling to be used on the mode of the card in question:

$$\text{IPUNCH} = \begin{cases} 0 \Rightarrow \text{lumped-resistive modelling (the usual case)} \\ 1 \Rightarrow \text{distortionless-mode modelling} \\ -1 \Rightarrow \text{frequency-dependent mode modelling (for zero seq. only);} \\ \quad\;\; \text{refer to Sec. 1.26b for extra data cards required.} \end{cases}$$

It is not obligatory to model the two modes of a multi-phase line the same way.

ITYPE	Node Names		Reference br.		Resistance R' [Ω/length]	A	B	Line length ℓ	ILINE	IPUNCH	IPOSE	IOUT
	BUS1	BUS2	BUS3	BUS4								
I2	A6	A6	A6	A6	E6.2	E6.2	E6.2	E6.2	I2	I2	I2	I1

Rule 9: IPOSE = { 0 or blank: Line is asumed to be transposed.
{ N : Number of phases of an untransposed line.

Rule 10: Only when IPOSE ≠ 0, the transformation matrix [Ti] is read immediately after the N-th branch card. The elements of the matrix [Ti] are read in by rows (row 1 first, then row 2, etc.). Within each row, elements are read in order of increasing column number. Each row begins with a new card, and there are 6 or fewer elements per card. The following format is applicable to row 'k' of a 6-phase line.

$T_{k,1}$	$T_{k,2}$	$T_{k,3}$	$T_{k,4}$	$T_{k,5}$	$T_{k,6}$
E12.5	E12.5	E12.5	E12.5	E12.5	E12.5

If the transmission line had only 3 phases, the final three fields (columns 37-72) would not be used. For $N \leq 6$ phases, exactly N data cards are involved; for $7 \leq N \leq 12$ phases, exactly 2N data cards are involved, etc. Note that there must be exactly N^2 elements for [Ti].

Example: Consider the 3-phase continuously-transposed line shown in the sketch above the preceding format rules. Suppose that line length is 180 miles, with parameters as follows:

	R' [ohm/mile]	L' [H/mile]	C' [μFd/mile]
Zero seq.	10.9	.0774	.0107
Pos. seq.	.0484	.0294	.0192

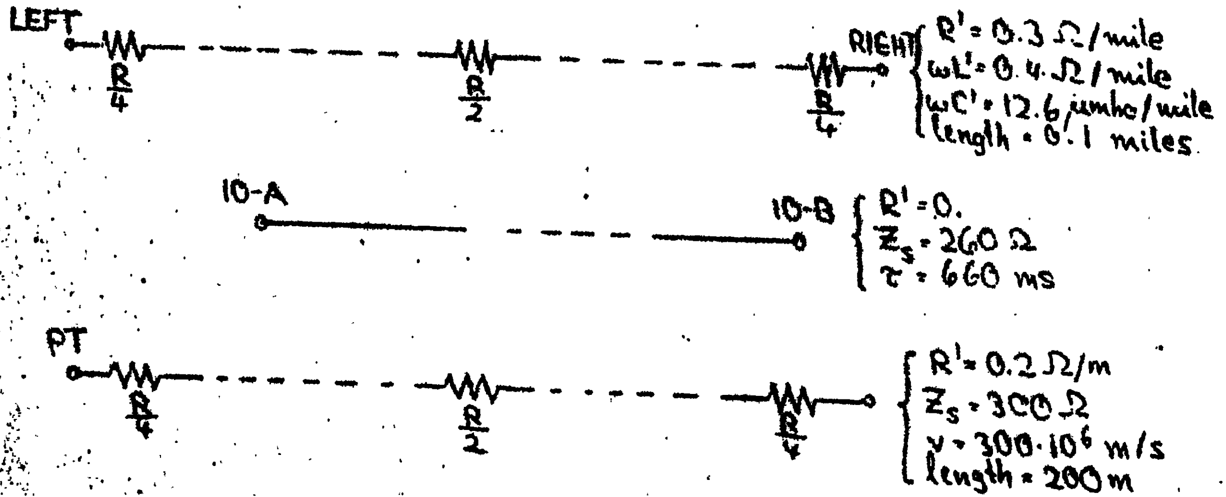
Corresponding data cards for input to the Transients Program then are:

```
-1GEN-A END-A             10.9  77.4 .0107  180.
-2GEN-B END-B            .0484  29.4 .0192  180.
-3GEN-C END-C
```

Example: Consider four separate, uncoupled single-phase lines, as per the sketches below. Corresponding input cards might then be as follows:

```
-1 LEFT RIGHT              0.3   0.4  12.6   0.1                             0
-1 10-A 10-B                    260.   .66                                   2
-1   PT   XY               0.2  300. 3.0E8  200.                             1
-1   L1   R1 LEFT  RIGHT
```

(assuming XOPT=60 and COPT=60 ; see floating-point miscellaneous data parameters, Section 1.0h):



Alternate high-precision format

The $VINTAGE card (see Section 1.-D), which is honored by most computer systems, provides for an alternate high-precision format. Specifically, the R,A,B,L fields can be switched to 4E12.0 (columns 27-74 in this case) if $VINTAGE, 1 precedes such a group of new branch cards, and $VINTAGE, 0 follows the grouping. As of August 1980, Pi-circuits (Section 1.23) and the simple series R-L-C branch (Section 1.21) are other components which allow such new, wider formats; they can also be included in the grouping between the $VINTAGE cards, then:

$VINTAGE, 1

> Any mixture of series R-L-C, Pi-circuit, and distributed line cards, as long as all use the new wide formats.

$VINTAGE, 0

ITYPE	BUS1	BUS2	Resistance R (Ω/length)	A	B	line length ℓ	ILINE	IPUNCH	IPOSE IOUT

The Section 1.26a is now eliminated from the EMTP Rule Book due to the removal of Karrenbauer's transformation for the transmission line from the EMTP.

Format for Frequency Cards (Point 4 "LINE CONSTANTS" data)

For each discrete frequency or logr'thmically-spaced grouping of frequencies for which lin constants are to be calculated, there is to be a frequency card of the following format:

Earth resistivity	frequency	Carson accuracy	Print [C]	Print [Z]		distance	Print Pi	MUTUAL				
RHO	FREQ	FCAR	ICPR	IZPR	[illegible]	DIST	IPIPR	[illegible]	IDEC	IPNT	IPUN	MODAL
F8.2	F10.2	F10.6	6I1	6I1	[illegible]	F8.3	4I1	[illegible]	I3	I3	I3	I2

RHO (1-8) ---- Resistivity of the homogeneous Carson earth, in units of ohm-meters . These units apply both to "METRIC" and "ENGLISH" data cases.

FREQ (9-18) ---- Frequency f of the line constants calculation, in units of Hertz . For logarithmic looping over two or more frequencies, this is the beginning frequency f_1 (see "IDEC" of columns 60-62).

FCAR (19-28) ---- Punch a "1" in column 28 , in order to get full precision in the evaluation of Carson's formula. This is the standard production usage. Other options are described elsewhere.

ICPR (30-35) ---- Printout control parameters for the capacitance matrices $[C]$, or the susceptance matrices $\omega[C]$, or the inverses of these. Variable "ICAP" of column 44 controls the inverse option, note. Six possible independent printed outputs can be requested by means of "1" punches in the appropriate columns:

Column #	Resulting printout
30	Inverse of $[C]$ or $\omega[C]$
31	Inverse of $[C_E]$ or $\omega[C_E]$
32	Inverse of $[C_S]$ or $\omega[C_S]$
33	$[C]$ or $\omega[C]$
34	$[C_E]$ or $\omega[C_E]$
35	$[C_S]$ or $\omega[C_S]$

Here subscripts (or lack of them) have meaning:

none ---- for the unreduced system. Each physical conductor has a row and column in th matrix, as does each ground wire.

"E" ---- for the equivalent phase conductors (after elimination of ground wires and the bundling of conductors).

"S" ---- for the symmetrical components of the equivalent phase conductors.

IZPR (37-42) ---- Printout control parameters for the series impedance matrices $[Z] = [R] + j\omega[L]$ or their inverses. Six possible independent printed outputs can be requested by means of "1" punches in the appropriate columns:

Col. #	37	38	39	40	41	42
Output	Z	Z_E	Z_S	Z^{-1}	Z_E^{-1}	Z_S^{-1}

ICAP (44) ---- Control over whether it is $[C]$ or $\omega[C]$ that will be outputted by any "ICPR" requests of columns 30-35 :

$$\begin{cases} 1 \Rightarrow [C] \text{ or its inverse} \\ 0 \Rightarrow \omega[C] \text{ or its inverse} \end{cases}$$

DIST (45-52) ---- Length of the transmission line under consideration, in units of

$$\begin{cases} \text{kilometers ---- if "METRIC"} \\ \text{miles ------- if "ENGLISH"} \end{cases}$$

This field can usually be left blank. It need be punched only for the following situations:

1) For use with "SEMLYEN SETUP" ; see Section 7.5
2) For the development of a Pi-equivalent using long-line formulas. See "IPIPR" below.

IPIPR (54-57) ---- Printout control for the equivalent-Pi matrices of a long transmission line. Four possible independent printed outputs can be requested by means of "1" punches in the appropriate columns:

Col. #	54	55	56	57
output	Y	Y_S	Z	Z_S

See further discussion elsewhere.

ISEG (58) ---- A flag indicating whether ground wires (if any) are to be treated as being continuous, or instead segmented:

$$\begin{cases} 0 \Rightarrow \text{continuous ground wires (the normal case);} \\ 1 \Rightarrow \text{segmented ground wires (cut at relatively short intervals).} \end{cases}$$

See further discussion elsewhere.

MUTUAL (59) —— A flag which is used to indicate the presence of communication circuit parallel to the power circuit:

- 0 ⟹ there is no such communication circuit (which is the normal case);
- 1 ⟹ yes, produce special output for a nearby communication circuit. See further discussion elsewhere.

IDEC (60-62) —— Leave blank for the normal single-frequency line constants calculation.

For the case of internal looping over logarithmically-spaced frequencies, "IDEC" is the number of decades which are to be spanned.

IPNT (63-65) —— Leave blank for the normal single-frequency line constants calculation.

For the case of internal looping over logarithmically-spaced frequencies, "IPNT" is the number of points per decade at which line constants are to be calculated.

IFUN (66-68) —— Normally this field is left blank. It is used to request non-printed output of modal quantities, in the case of internal looping over logarithmically-spaced frequencies. Punch :

- "88" —— For the connection of zero-sequence (ground mode) impedances with "WEIGHTING". This has meaning only when a "LINE CONSTANTS" data case is imbedded in a "WEIGHTING" data case.
- "89" —— As just described for "88", only for the Karrenbauer line mode (rather than the ground mode).

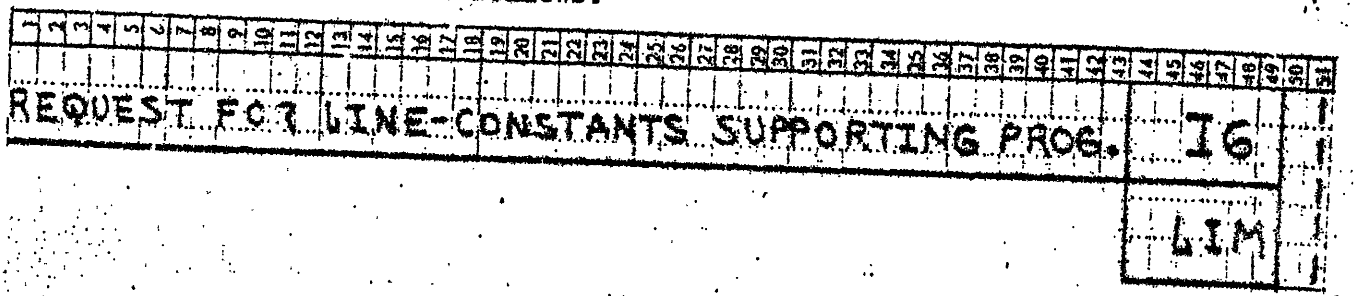
MODAL (69-70) ——

- 0 or blank ⟹ The line is assumed to be continuously-transposed.
- 1 ⟹ The line is assumed to be untransposed. The modal parameters and transformation matrix will be calculated and written on unit LUNIT7 as branch data (see Section 1.26).

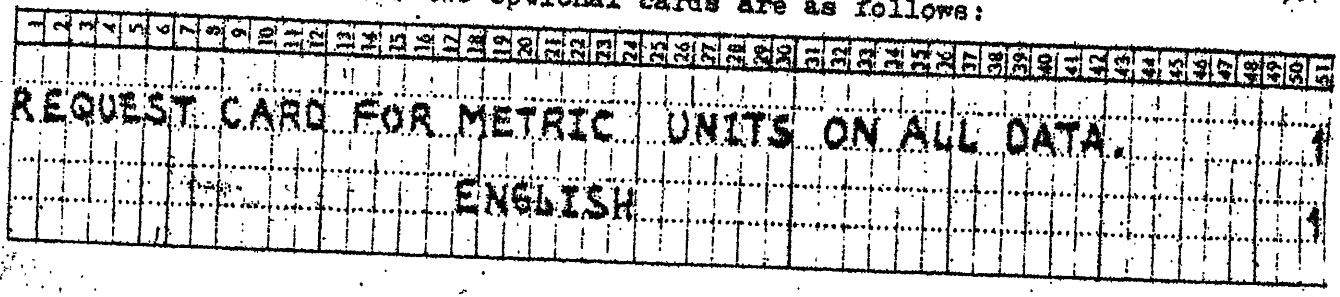
Interpretation of Input Data Cards

As explained in Section 2 1 , input data cards are listed in columns 52-131 of the line printer; a "1" is printed in column 51 as a separator character, and columns 1-50 are used for "interpretation" of the card image. All interpretations related to "LINE CONSTANTS" are explained in the present section.

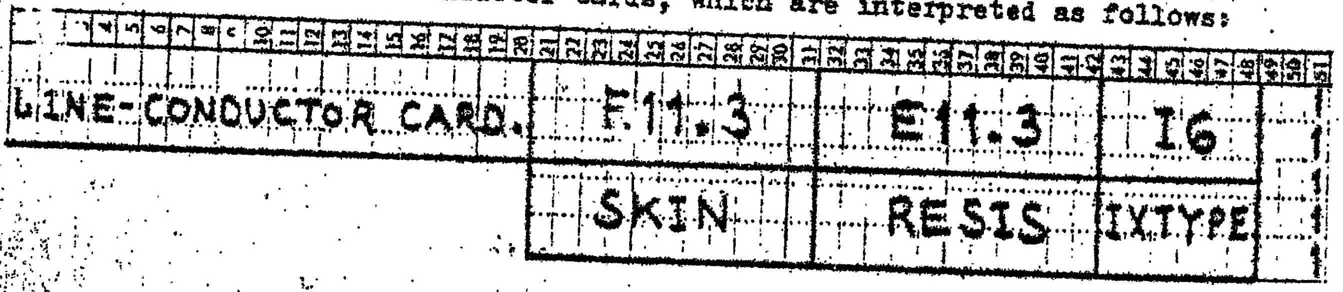
First, there is the special request card which bears the key word "LINE CONSTANTS" (see Section 1.0g) . If we let variable "LIM" stand for the maximum number of line conductors that current EMTP dimensioning will allow, interpretation is as follows:



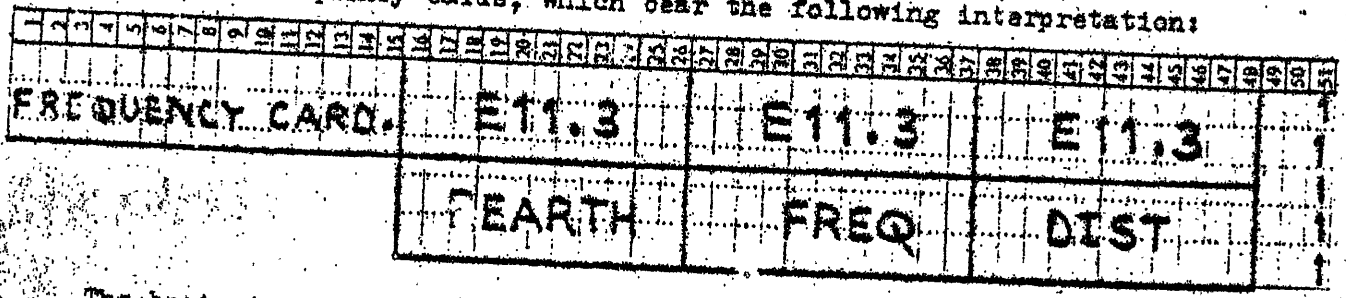
Next comes a possible "METRIC" or "ENGLISH" special request card (which serves to request either metric or English units for input/output data). Interpretations of these two optional cards are as follows:



Next come the line conductor cards, which are interpreted as follows:



Next come frequency cards, which bear the following interpretation:



The beginning of a change case is a special-request card which bears the key word "CHANGE" . This is interpreted as follows: